Supporting Information

Hydrazone exchange: a viable route for the solid-tethered synthesis of [2]rotaxanes.

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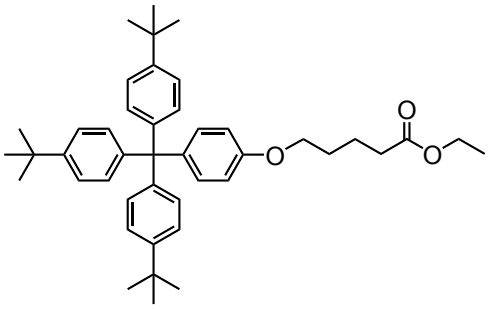
1. Experimental details and HPLC and LC MS methods

General considerations

Unless otherwise stated, reagents were purchased from commercial sources (*e.g.* Sigma Aldrich, Alfa Aesar, CTI) and used without further purification. The following solvents (AR grade) were distilled and dried prior to use according to standard procedures: acetonitrile, tetrahydrofuran and *N,N*-dimethylformamide were purified by a solvent purification system - Innovative Technologies PureSolv Micro; ethyl acetate, methanol and hexane were distilled under reduced pressure. Triethylamine was dried over KOH. All silica gel column chromatography was performed using Merck silica gel 60 (grade 9835, 230-400 mesh). Analytical TLC was carried out on Merck silica gel F_{254} precoated aluminium sheets. The TentaGel™ S-NHNHBoc resins were purchased from Rapp-polymere with a quoted loading of 0.27 mmol/g and size of 130 μm. Solution NMR spectra were recorded on a Bruker Avance 400 MHz or a Bruker Avance 600 MHz spectrometer and referenced to the relevant solvent peak. High resolution magic angle spinning NMR spectra were recorded on a Bruker Avance 400 MHz spectrometer at 298 K using a Bruker HR MAS probe. Rotors containing a suspension of the beads in $CDCl_3$, acetone-d_6 or CD_3CN were spun at 4 or 5 kHz. One-dimensional HR MAS spectra were obtained with 64 scans. Unless otherwise stated, the CPMG pulse sequences used contained either 0, 8, 32 or 128 π-pulses with a repetition time of 30 ms. A Dionex Ultimate 3000 RSLC was used for HPLC separations. ESI high-resolution mass spectra were obtained using a Thermo Fisher Scientific Orbitrap Elite™ mass spectrometer equipped with a heated electrospray ionisation source operating in the positive ion mode. UV-visible spectra were recorded on a Shimadzu UV-1800 UV-vis spectrophotometer. IR spectra were obtained using a Thermo Nicolet Nexus 870 esp spectrometer equipped with a 45° Ge ATR accessory at 4 cm^{-1} resolution using 64 scan averaging. Melting points were measured by the capillary method on a Gallen Kamp variable-temperature melting point apparatus and are uncorrected.

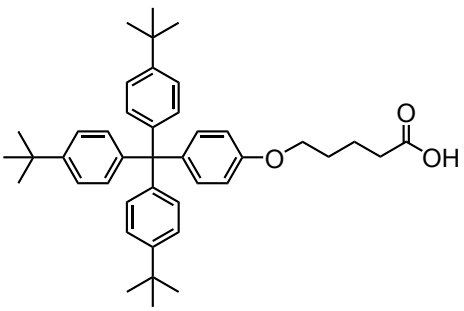
Synthetic procedures

Synthesis of ethyl 5-(4-(tris(4-(*tert*-butyl)phenyl)methyl)phenoxy)pentanoate



Phenol stopper[1] **7** (113 mg, 0.22 mmol), K_2CO_3 (38 mg, 0.22 mmol), and Cs_2CO_3 (40 mg, 0.11 mmol) were suspended in dry, degassed MeCN (100 mL). Ethyl (5-bromo)valerate (75 µL, 0.45 mmol) was then added, and the reaction mixture brought to a steady reflux for 7 days. The reaction mixture was then filtered through Celite and the solvent evaporated. The product was dissolved in CH_2Cl_2 and washed with 1 M HCl (2 × 50 mL) and water (2 × 50 mL). The crude residue was purified by column chromatography over silica using CH_2Cl_2:hexane (80:20) as the eluent to give the pure product as a white solid (140 mg, 98%). m/z (ESI-MS) $[M+Na]^+$ 655.412 $C_{44}H_{56}O_3$ (calc. 655.4122, Δ = -0.4 ppm). m.p.: 147 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25 – 7.20 (m, 6H), 7.07 (dd, J_{HH} = 8.7, 4.3 Hz, 8H), 6.74 (d, J_{HH} = 8.8 Hz, 2H), 3.95 (t, J_{HH} = 5.6 Hz, 2H), 3.10 (qd, J_{HH} = 7.3, 4.9 Hz, 2H), 2.31 (t, J_{HH} = 6.9 Hz, 2H), 1.89 – 1.80 (m, 4H), 1.41 (t, J_{HH} = 7.3 Hz, 3H), 1.30 (s, 27H). ^{13}C NMR (151 MHz, $CDCl_3$): δ 149.9, 148.4, 144.3, 132.4, 130.9, 127.7, 124.8, 124.1, 113.0, 67.3, 63.2, 51.7, 34.6, 34.4, 33.8, 31.5, 28.9, 21.8. Purity determined by HPLC-MS: >99%. Anal. Calcd for $C_{44}H_{56}O_3$: C, 83.5; H, 8.92. Found: C, 83.63; H, 8.89.

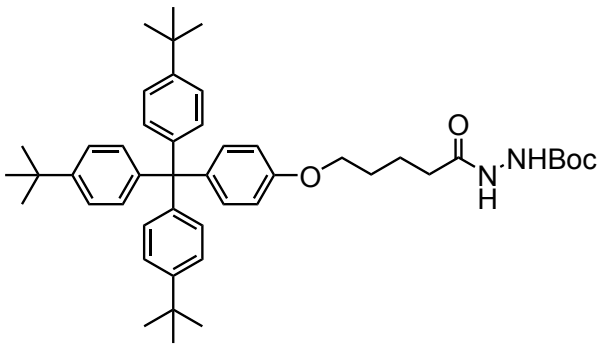
Synthesis of 5-(4-(Tris(4-(*tert*-butyl)phenyl)methyl)phenoxy)pentanoic acid 8



Compound **8** was synthesised following a modified literature procedure.[2] Ethyl 5-(4-(tris(4-(*tert*-butyl)phenyl)methyl)phenoxy)pentanoate (692 mg, 1.1 mmol) was dissolved in CH_2Cl_2 (10 mL) and stirred while a saturated solution of NaOH in MeOH (1 mL) was added to the reaction. The reaction was stirred for 1 h before being quenched with ice cold HCl ($20\%_{(aq)}$, 50 mL). The

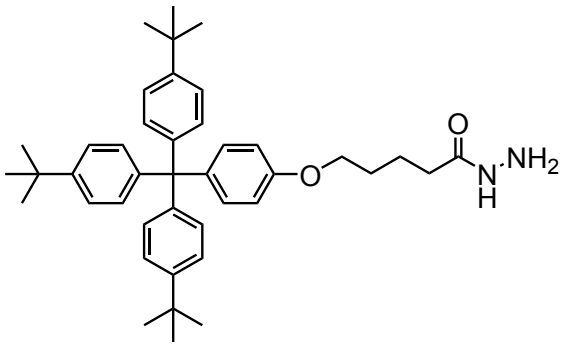
product was then extracted with CH_2Cl_2 (3 × 100 mL). The organic extracts were combined and evaporated. The crude solid was purified by column chromatography using $CHCl_3$/MeOH (96:4) as the eluent to afford the pure product as a white solid (655 mg, 99%). m.p. 218 °C. m/z (ESI-MS) $[M-H]^-$ 603.3841 $C_{42}H_{52}O_3$ (calc. 603.3844, Δ = -0.4 ppm). ^1H NMR (400 MHz, $CDCl_3$): δ 7.23 (d, J_{HH} = 8.6 Hz, 6H), 7.07 (dd, J_{HH} = 8.7, 3.5 Hz, 8H), 6.75 (d, J_{HH} = 8.9 Hz, 2H), 3.99 – 3.90 (m, 2H), 2.47 – 2.43 (m, 2H), 1.83 (m, J_{HH} = 3.1 Hz, 4H), 1.30 (s, 27H). ^{13}C NMR (151 MHz, $CDCl_3$): δ 156.6, 148.4, 144.3, 132.4, 130.9, 127.6, 124.6, 124.2, 113.0, 67.3, 63.2, 51.7, 34.4, 31.5, 28.9, 21.6. Purity determined by HPLC-MS: >99%.

Synthesis of Boc protected hydrazide stopper 9



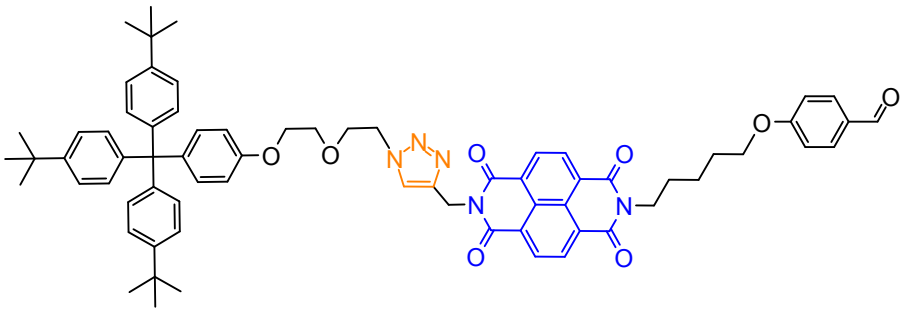
Compound **9** was synthesised following a modified literature procedure.[3] Thionyl chloride (0.08 mL, 1.3 mmol) was added to a solution of acid stopper **8** (650 mg, 1.1 mmol) in toluene (30 mL). The reaction was refluxed overnight. The solvent was then removed *in vacuo*. The crude white solid was reacted immediately by dissolving in dry degassed CH_2Cl_2 (20 mL), to which *tert*-butyl carbazate (140 mg, 1.3 mmol) was added. The reaction was then stirred at room temperature for two days under argon. The solvent was then evaporated and the crude residue was purified by column chromatography using CH_2Cl_2:MeOH (97:3) as the eluent to give the pure product as a white solid (250 mg, 32%). m.p.: 206 °C. m/z (ESI-MS) $[M+H]^+$ 719.478 $C_{47}H_{62}N_2O_4$ (calc. 719.4782, Δ = -0.4ppm). ^1H NMR (600 MHz, $CDCl_3$): δ 7.23 (d, J_{HH} = 8.5 Hz, 6H), 7.10 – 7.05 (m, 8H), 6.74 (d, J_{HH} = 8.9 Hz, 2H), 3.96 (t, J_{HH} = 5.6 Hz, 2H), 2.31 (t, J_{HH} = 6.9 Hz, 2H), 1.86 (m, 6H), 1.30 (s, 27H). ^{13}C NMR (151 MHz, $CDCl_3$): δ 172.2, 156.6, 148.3, 144.1, 139.6, 132.3, 130.7, 124.0, 112.9, 81.9, 67.3, 63.0, 34.3, 33.7, 31.4, 28.1, 22.2. Purity determined by HPLC-MS: >99%.

Synthesis of hydrazide stopper 3



The Boc-protected hydrazide stopper **9** (900 mg, 1.5 mmol) was dissolved in a solution of 50:50 TFA:$CHCl_3$ (50 mL) and stirred at room temperature for 45 min. After this time the solution was neutralised with $CHCl_3$:TEA (95:5). The organic layer was then washed with sat. $NaHCO_{3(aq)}$ (2 × 30 mL) and water (2 × 30 mL), before being dried over Na_2SO_4 and the solvent removed. The crude residue was purified by column chromatography using CH_2Cl_2:EtOAc (90:10 to 70:30) as the eluent to afford the product as a white solid (774 mg, 99%). m/z (ESI-MS) $[M+Na]^+$ 641.4073 $C_{42}H_{54}N_2O_2$ (calc. 641.4078, Δ = -0.8ppm). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.10 (s, 1H), 7.22 (d, J_{HH} = 8.6 Hz, 6H), 7.07 (d, J_{HH} = 7.7 Hz, 8H), 6.74 (d, J_{HH} = 8.5 Hz, 2H), 3.95 (t, J_{HH} = 5.7 Hz, 2H), 2.34 (t, J_{HH} = 7.0 Hz, 2H), 1.96 – 1.75 (m, 4H), 1.29 (s, 27H). This compound was deprotected and used immediately in any exchange reactions to avoid dimerization (Figure S2).

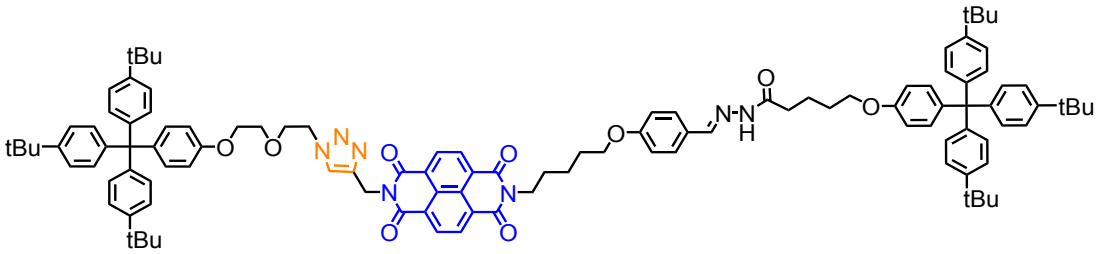
Synthesis of NDI aldehyde 4



The tosyl NDI half-dumbbell[4] **10** (260 mg, 0.25 mmol) was dissolved in dry degassed MeCN (30 mL). p-Hydroxybenzaldehyde (84 mg, 0.75 mmol), potassium carbonate (40 mg, 290 mmol) and caesium carbonate (cat.), were added and the reaction mixture was refluxed for 3 days, before being filtered and the solvent removed *in vacuo*. The crude solid was then purified by column chromatography using CH_2Cl_2:MeOH (99:1 to 98:2) to afford the pure product as a yellow solid (232 mg, 85%). m.p.: 187 °C. m/z (ESI-MS) $[M+Na]^+$ 1134.5357 $C_{70}H_{73}N_5O_8$ (calc. 1134.5351, Δ = 0.5 ppm). ^{1}H NMR (400 MHz, $CDCl_3$): δ 9.86 (s, 1H), 8.73 (q, J_{HH} = 7.6 Hz, 4H), 7.86 (s, 1H), 7.80 (d, J_{HH} = 8.7 Hz, 2H), 7.23 (d, J_{HH} = 8.6 Hz, 4H), 7.12 (d, J_{HH} = 8.9 Hz, 2H),

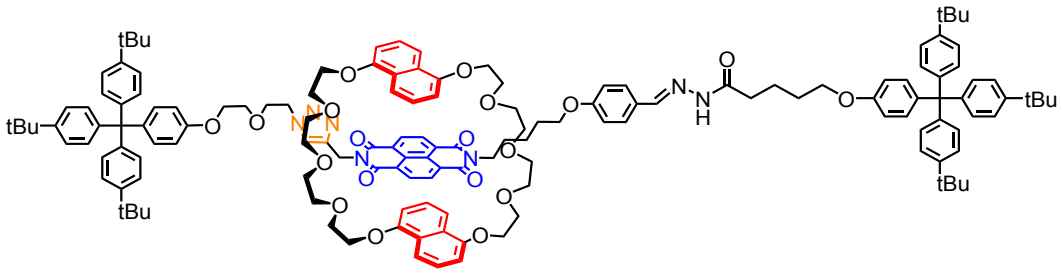
7.08 (d, J_{HH} = 8.6 Hz, 4H), 6.97 (d, J_{HH} = 8.7 Hz, 2H), 6.79 (d, J_{HH} = 8.9 Hz, 2H), 5.48 (s, 2H), 4.52 (t, J_{HH} = 5.0 Hz, 2H), 4.26 – 4.20 (m, 2H), 4.09 – 4.04 (m, 4H), 3.90 (t, J_{HH} = 5.0 Hz, 2H), 3.77 (d, J_{HH} = 4.5 Hz, 2H), 1.91 (p, J_{HH} = 6.6 Hz, 2H), 1.84 (d, J_{HH} = 10.3 Hz, 2H), 1.28 (s, 27H). ^{13}C NMR (151 MHz, $CDCl_3$): δ 190.9, 164.2, 162.9, 162.7, 156.4, 148.5, 148.4, 144.3, 144.2, 140.3, 132.5, 132.4, 132.1, 131.4, 131.1, 130.8, 129.9, 127.0, 126.8, 126.7, 124.2, 114.9, 113.2, 113.0, 70.0, 69.6, 68.1, 67.2, 63.2, 50.5, 40.8, 35.4, 34.4, 31.5, 28.9, 27.9, 23.6. Purity determined by HPLC-MS: >99%.

Large scale synthesis of NDI hydrazone dumbbell 11



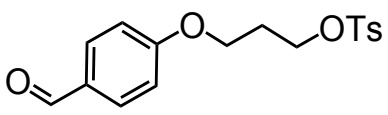
NDI aldehyde **4** (101 mg, 0.1 mmol) and hydrazide stopper **3** (57.2 mg, 0.1 mmol) were dissolved in a solution of TFA in $CHCl_3$ (0.05 % v/v, 10 mL). The reaction mixture was stirred for 7 days. After this time the reaction was quenched with TEA (0.5 mL) in $CHCl_3$ (5 mL), diluted in $CHCl_3$ (50 mL) and washed with water (3 × 20 mL). The organic fractions were dried over Na_2SO_4 and the solvent was evaporated under vacuum. The crude product was purified by column chromatography over silica (treated with TEA) using $CHCl_3$:MeOH (99:1) as eluent to give the pure product as a cream solid (83 mg, 52%). m.p.: 205 °C. m/z (ESI-MS) $[M+H]^+$ 1712.9655 $C_{112}H_{126}N_7O_9$ (calc. 1712.9612, Δ = -0.5 ppm). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.73 (q, J_{HH} = 7.6 Hz, 4H), 7.86 (s, 1H), 7.63 (d, J_{HH} = 6.7 Hz, 1H), 7.51 (d, J_{HH} = 8.6 Hz, 2H), 7.22 (ddd, J_{HH} = 8.7, 4.6, 2.0 Hz, 12H), 7.12 (d, J_{HH} = 8.9 Hz, 2H), 7.08 (ddd, J_{HH} = 10.2, 7.8, 5.1 Hz, 14H), 6.84 (d, J_{HH} = 8.8 Hz, 2H), 6.79 (d, J_{HH} = 9.0 Hz, 2H), 6.75 (d, J_{HH} = 8.9 Hz, 2H), 5.48 (s, 2H), 4.52 (t, J_{HH} = 5.0 Hz, 2H), 4.23 (dd, J_{HH} = 8.7, 6.5 Hz, 2H), 4.09 – 4.04 (m, 2H), 3.98 (q, J_{HH} = 6.4 Hz, 4H), 3.91 (t, J_{HH} = 5.0 Hz, 2H), 3.79 – 3.75 (m, 2H), 2.82 (t, J_{HH} = 6.9 Hz, 2H), 2.35 (t, J_{HH} = 7.0 Hz, 2H), 1.94 – 1.78 (m, 8H), 1.66 – 1.57 (m, 2H), 1.29 (s, 27H), 1.29 (s, 27H). ^{13}C NMR (151 MHz, $CDCl_3$): δ 162.9, 162.6, 160.8, 157.0, 156.5, 148.5, 148.4, 148.4, 144.3, 144.3, 144.2, 142.8, 140.2, 139.5, 132.5, 132.4, 132.3, 131.3, 131.1, 130.9, 130.8, 128.7, 126.9, 126.8, 126.7, 124.7, 124.2, 124.2, 114.8, 113.2, 113.1, 70.0, 69.7, 67.8, 67.5, 67.4, 67.2, 63.2, 61.1, 50.4, 40.9, 35.7, 34.4, 33.8, 32.5, 31.5, 29.1, 28.7, 23.6, 22.4, 21.5. Purity determined by HPLC-MS: >99%.

Large scale synthesis of naphthalene diimide rotaxane 6



NDI aldehyde **4** (101 mg, 0.09 mmol), hydrazide stopper **3** (57.2 mg, 0.09 mmol) and 1,5-dinaphtho[38]crown-10[5] **5** (286 mg, 0.45 mmol) were dissolved in a solution of TFA and $CHCl_3$ (10 mL, 0.05 % v/v). The reaction was then stirred for 7 days before being quenched with TEA (0.5 mL) in $CHCl_3$ (5 mL), diluted in $CHCl_3$ (50 mL) and washed with water (3 × 20 mL). The organic fraction was dried over Na_2SO_4 and the solvent was evaporated. The crude product was then purified by silica (treated with TEA) column chromatography using $CHCl_3$:MeOH (99:1) as the eluent to yield the rotaxane as a red solid (73 mg, 35%). m.p.: 118 °C. m/z (ESI-MS) $[M+H]^+$ 2349.2587 $C_{112}H_{126}N_7O_9$ (calc. 2349.2546, Δ = -1.7ppm). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.72 (d, J_{HH} = 10.4 Hz, 1H), 8.33 – 8.21 (m, 4H), 8.07 (d, J_{HH} = 3.9 Hz, 1H), 7.64 (s, 1H), 7.59 (d, J_{HH} = 8.7 Hz, 2H), 7.25 – 7.20 (m, 12H), 7.11 – 7.04 (m, 16H), 6.95 (t, J_{HH} = 8.2 Hz, 2H), 6.79 (t, J_{HH} = 8.5 Hz, 4H), 6.77 – 6.74 (m, 2H), 6.73 (dd, J_{HH} = 9.1, 2.5 Hz, 2H), 6.42 (t, J_{HH} = 7.7 Hz, 4H), 5.96 (dd, J_{HH} = 15.0, 7.6 Hz, 4H), 5.39 (s, 2H), 4.64 (dd, J_{HH} = 9.7, 4.7 Hz, 2H), 4.12 (t, J_{HH} = 6.2 Hz, 2H), 4.10 – 4.05 (m, 4H), 4.03 – 3.94 (m, 10H), 3.93 – 3.89 (m, 8H), 3.84 (t, J_{HH} = 16.7 Hz, 20H), 3.78 – 3.73 (m, 4H), 2.82 (t, J_{HH} = 6.9 Hz, 2H), 2.03 (dt, J_{HH} = 21.4, 6.9 Hz, 4H), 1.98 – 1.87 (m, 8H), 1.79 (dd, J_{HH} = 30.3, 22.4 Hz, 4H), 1.30 (s, 27H), 1.29 (s, 27H). ^{13}C NMR (151 MHz, $CDCl_3$): δ 163.2, 162.8, 160.9, 156.9, 156.4, 153.1, 148.5, 148.4, 144.3, 144.2, 143.2, 143.1, 140.1, 139.5, 132.4, 132.3, 130.8,* 130.7, 128.8,* 125.7, 125.2, 125.1, 124.8, 124.2, 123.6, 115.0, 114.2, 113.1, 103.5, 71.5*, 71.3, 70.0, 69.9, 68.1, 67.5, 67.1, 63.2, 60.5, 50.6, 40.4, 34.8, 34.4, 32.5, 31.5, 29.8, 29.2, 27.9, 27.8, 24.2, 21.4, 21.3, 21.2, 14.5. Purity determined by HPLC-MS: >98%. (*overlapping ^{13}C signals from crown ether)

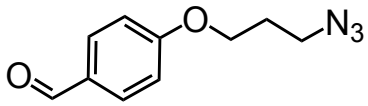
Synthesis of 3-(4-formylphenoxy)propanol *p*-toluenesulfonate



3-(4-Formylphenoxy)propanol *p*-toluenesulfonate was synthesised according to literature procedures, and its characterisation matches literature reports.[6] 4-(3-hydroxypropoxy)benzaldehyde[6] **12** (300 mg, 5 mmol), triethylamine (1.0 mL, 7.0 mmol) and 4,4-dimethylaminopyridine (cat.) were dissolved in dry degassed CH_2Cl_2 (10 mL). A solution of

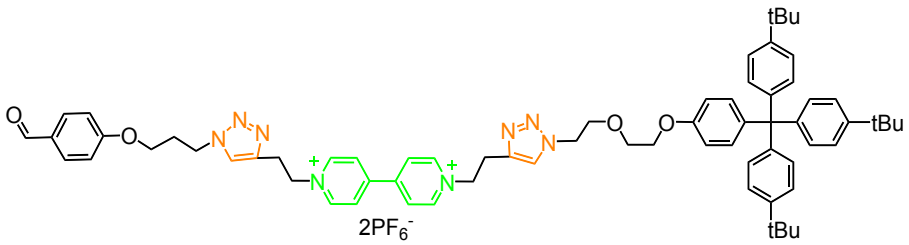
tosyl chloride (631 mg, 10.1 mmol) in CH_2Cl_2 (10 mL) was added gradually to the reaction over 20 min at 0 °C. The reaction was then brought to room temperature and stirred for 3 days. The solution was then diluted with CH_2Cl_2 (30 mL) and washed with 1 M HCl (30 mL) and water (2 × 50 mL). The product was then purified by column chromatography using CH_2Cl_2 as eluent (372 mg, 67%). m/z (ESI-MS) $[M+Na]^+$ 357.0766 $C_{17}H_{18}O_5S$ (calc. 357.0767, Δ = -0.4 ppm). ^{1}H NMR (400 MHz, $CDCl_3$): δ 9.89 (s, 1H), 7.81 (d, J_{HH} = 8.7 Hz, 2H), 7.75 (d, J_{HH} = 8.2 Hz, 2H), 7.25 (td, J_{HH} = 7.3, 0.5 Hz, 2H), 6.87 (d, J_{HH} = 8.7 Hz, 2H), 4.25 (t, J_{HH} = 5.9 Hz, 2H), 4.04 (t, J_{HH} = 5.8 Hz, 2H), 2.36 (s, 3H), 2.16 (p, J_{HH} = 5.9 Hz, 2H). ^{13}C NMR (151 MHz, $CDCl_3$): δ 190.9, 163.6, 145.0, 132.8, 132.0, 130.2, 130.0, 127.9, 114.7, 66.7, 63.6, 28.8, 21.8. Purity determined by HPLC-MS: >98%.

Synthesis of 4-(3-azidopropoxy)benzaldehyde 13



3-(4-Formylphenoxy)propanol *p*-toluenesulfonate[6] (264 mg, 0.79 mmol) and sodium azide (760 mg, 11.7 mmol) were dissolved in dry DMF (20 mL) and heated at 120 °C for 3 days. The solvent was then evaporated and the residue dissolved in CH_2Cl_2 (50 mL) and washed with water (3 × 30mL). The yellowish white residue was purified by column chromatography using CH_2Cl_2 as the eluent (156 mg, 96%). m/z (ESI-MS) $[M+Na]^+$ 228.0742 $C_{10}H_{11}N_3O_2$ (calc. 22.0743, Δ = -0.4 ppm). ^{1}H NMR (400 MHz, $CDCl_3$): δ 9.89 (s, 1H), 7.84 (d, J_{HH} = 8.8 Hz, 2H), 7.01 (d, J_{HH} = 8.7 Hz, 2H), 4.14 (t, J_{HH} = 5.9 Hz, 2H), 3.54 (t, J_{HH} = 6.6 Hz, 3H), 2.09 (p, J_{HH} = 6.4 Hz, 2H). ^{13}C NMR (151 MHz, $CDCl_3$): δ 190.9, 163.8, 132.2, 130.3, 114.9, 65.0, 48.2, 28.7. Purity determined by HPLC-MS: >98%.

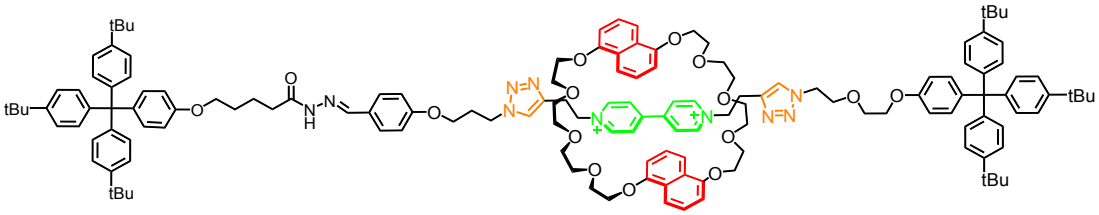
Synthesis of bipyridinium aldehyde 15.2PF_6^-



Alkyne bipyridinium half-dumbbell[1] **14.2PF_6^-** (100.8 mg, 0.86 mmol) and aldehyde **13** (17.6 mg, 0.085 mmol) were dissolved in dry degassed acetone (20 mL). $Cu(MeCN)_4PF_6$ (cat.)

and TBTA (cat.) were then added and the reaction stirred for 5 days. After this time, the solution was diluted in CH_2Cl_2 (100 mL) and washed with water (3 × 50 mL). The organic phase was evaporated under reduced pressure. The product was isolated by purification by column chromatography using MeOH:$MeNO_2$:NH_4PF_6(2 M) (75:24:1) as eluent (69.2 mg, 58% yield). m.p.: 256 °C. m/z (ESI-MS) $[M\text{-}PF_6]^+$ 1229.5903 $C_{69}H_{80}F_6N_8O_4P$ (calc. 1229.5939, Δ = 3.0ppm). ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.80 (d, *J* = 2.8 Hz, 1H), 8.84 – 8.71 (m, 4H), 8.30 – 8.19 (m, 4H), 7.74 (dd, *J* = 8.6, 2.7 Hz, 2H), 7.36 (d, *J* = 2.8 Hz, 1H), 7.22 (dd, *J* = 8.6, 2.8 Hz, 6H), 7.16 – 7.03 (m, 9H), 6.94 (dd, *J* = 8.7, 2.7 Hz, 2H), 6.75 – 6.67 (m, 2H), 5.02 – 4.89 (m, 4H), 4.57 – 4.40 (m, 4H), 4.01 (ddt, *J* = 11.5, 8.1, 4.0 Hz, 4H), 3.91 – 3.83 (m, 2H), 3.75 (dt, *J* = 6.5, 3.0 Hz, 2H), 3.46 – 3.34 (m, 4H), 2.33 (d, *J* = 7.2 Hz, 2H), 1.28 (s, 27H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 191.9, 164.7, 157.2, 151.6, 151.5, 149.2, 146.7, 146.0, 145.9, 142.7, 142.6, 140.9, 132.5, 131.0, 128.3, 128.1, 126.8, 125.0, 124.9, 123.7, 115.7, 114.6, 70.1, 67.3, 66.4, 64.3, 62.2, 62.1, 52.2, 47.9, 34.9, 31.9, 30.0, 28.0, 27.9, 27.8. ^{19}F (565 MHz, $CDCl_3$): -71.97. Purity determined by HPLC-MS: >98%.

Synthesis of bipyridinium [2]rotaxane 17.2PF_6^-



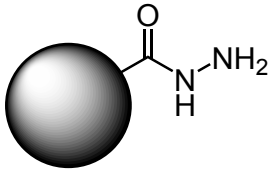
Bipyridinium aldehyde **15.2PF_6^-** (70 mg, 0.05 mmol), hydrazide stopper **3** (32 mg, 0.05 mmol) and 1,5-dinaphtho[38]crown-10 **5** (165 mg, 0.25 mmol) were dissolved in a solution of TFA and $CHCl_3$ (10 mL, 0.05 % v/v). The reaction was stirred for 7 days before being quenched with $Na_2CO_{3(aq)}$ (5 mL), diluted in $CHCl_3$ (5 mL), and washed with water (10 mL) and $NH_4PF_{6(aq)}$ (10 mL). The organic fraction was dried over Na_2SO_4 and the solvent was evaporated under vacuum. The crude solid was purified by column chromatography using MeOH:$MeNO_2$:$NH_4PF_{6(aq)}$ (74:25:1) as the eluent to afford the product as a red solid (15 mg, 12%). m/z (ESI-MS) $[M - 2PF_6]^{2+}$ 1160.6639 $C_{147}H_{174}N_{10}O_{15}$ (calc. 1160.6653, Δ = -1.2 ppm). ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.57 (m, 4H), 8.49 (s, 1H), 7.98 (s, 1H), 7.91 (s, 1H), 7.60 (s, 1H), 7.55 (d, J_{HH} = 8.6 Hz, 2H), 7.22 (dd, J_{HH} = 15.5, 7.0 Hz, 12H), 7.18 (d, J_{HH} = 9.0 Hz, 2H), 7.10 – 7.02 (m, 16H), 6.99 (d, J_{HH} = 5.6 Hz, 4H), 6.90 (d, J_{HH} = 8.7 Hz, 2H), 6.77 (d, J_{HH} = 8.9 Hz, 2H), 6.76 – 6.72 (m, 2H), 6.50 (t, J_{HH} = 7.4 Hz, 4H), 5.01 (s, 4H), 4.66 – 4.55 (m, 4H), 4.13 – 4.08 (m, 2H), 4.07 – 4.01 (m, 2H), 3.98 (d, J_{HH} = 2.7 Hz, 4H), 3.95 – 3.80 (m, 24H), 3.76 (m, 4H), 3.52 (s,

4H), 2.80 (d, J_{HH} = 6.5 Hz, 2H), 2.44 (dd, J_{HH} = 12.1, 6.2 Hz, 2H), 1.87 (dd, J_{HH} = 20.1, 5.4 Hz, 4H), 1.29 (s, J_{HH} = 4.1 Hz, 27H), 1.28 (s, 27H). ^{19}F NMR (565 MHz, $CDCl_3$): δ -71.43.

General bead washing procedure for hydrazide and hydrazone beads

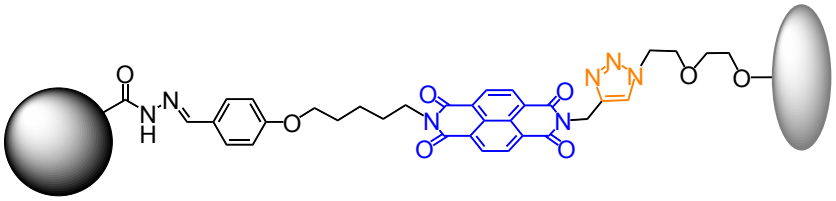
Following reaction all TentaGel™ beads were then washed alternatively with CH_2Cl_2 (2 × 1 mL) followed by 5 cycles of alternating hexane (2 × 1 mL)/CH_2Cl_2 (2 × 1 mL) washes, terminating on a wash with CH_2Cl_2 (2 × 1 mL). This cycle of washing was designed to shrink and swell the beads to ensure complete removal of any residual material from the reaction solution. The beads were finally washed with methanol (2 × 1 mL), water (5 × 1 mL), methanol (5 × 1mL) and finally CH_2Cl_2 (5 × 1 mL) before being dried.

TentaGel™-CONHNH$_2$ functionalised resins 19



The TentaGel™ –CONHNHBoc resins **18** were suspended in $CHCl_3$:TFA (50:50) for 30 min. The solution was then neutralised with a solution of $CHCl_3$:TEA (80:20) and the solvent was filtered through a fritted funnel. The beads were then washed according to the general procedure for hydrazide beads before being dried. HR MAS ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.21 (bs, 1H), 4.54 (bs, 1H), 2.43 (d, J_{HH} = 5.1 Hz, 2H), 2.39 (d, J_{HH} = 5.7 Hz, 2H).

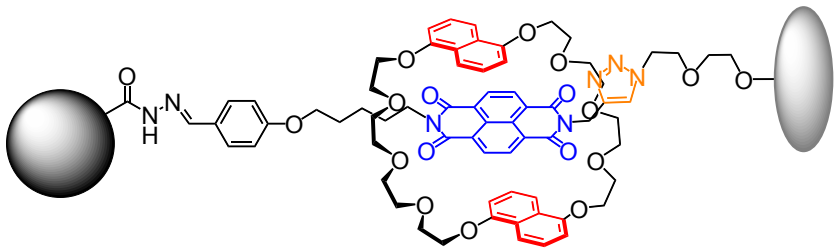
Synthesis of beads functionalised with NDI dumbbell 20



NDI aldehyde half dumbbell **4** (22.5 mg, 2.0 × 10^{-2} mmol) was added to a suspension of the TentaGel™ –CONHNH$_2$ resins **19** (0.27 mmol/g, 14.8 mg, 4 × 10^{-3} mmol) in $CHCl_3$ (4 mL) in the presence of TFA (0.01% v/v). The suspension was stirred periodically for 7 days. The reaction was then quenched with TEA (1% v/v) in $CHCl_3$ (2 mL). The beads were then washed according to the general procedure for hydrazone beads before being dried. HR-MAS ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.85 – 8.69 (m, 4H), 8.19 (s, J_{HH} = 29.6 Hz, 1H), 7.92 (s, 2H), 7.27 (d, J_{HH} = 13.4 Hz, 6H), 7.12 (d, J_{HH} = 8.1 Hz, 8H), 6.82 (d, J_{HH} = 8.4 Hz, 2H), 5.33 (s, 1H), 4.87 (s, 2H), 4.75 (s,

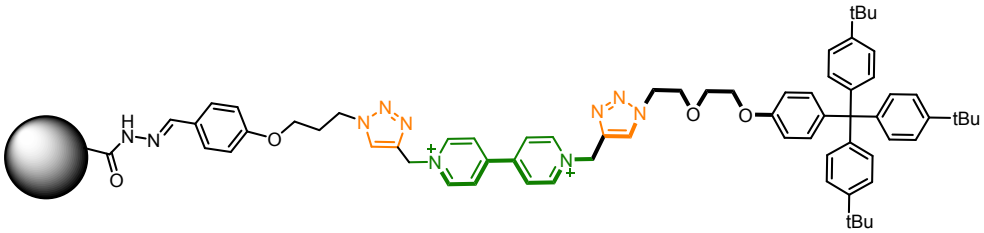
2H), 4.39 – 4.31 (m, 2H), 3.00 (t, J_{HH} = 6.6 Hz, 2H), 2.92 (t, J_{HH} = 7.3 Hz, 2H), 2.69 – 2.51 (m, 8H), 1.32 (s, J_{HH} = 9.1 Hz).

Synthesis of NDI rotaxane functionalised resins 1



NDI aldehyde half dumbbell **4** (22.6 mg, 20 µmol) and 1,5-dinaphtho[38]crown-10 **5** (64.7 mg, 100 µmol) were added to a suspension of the TentaGel™ –$CONHNH_2$ resins **19** (0.27 mmol/g, 15.0 mg, 4 µmol) in $CHCl_3$ (4 mL) in the presence of TFA (0.01% v/v). The suspension was stirred periodically for 7 days. The reaction was then quenched with TEA (1% v/v) in $CHCl_3$ (2 mL). The beads were then washed according to the general procedure for hydrazide beads before being dried. HR-MAS ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.70 – 8.57 (m, 4H), 8.18 (d, J_{HH} = 3.9 Hz, 4H), 8.07 (s, 1H), 8.01 (s, 1H), 7.52 (d, J_{HH} = 8.1 Hz, 2H), 7.21 – 7.10 (m, 6H), 6.96 (d, J_{HH} = 7.7 Hz, 8H), 6.70 (d, J_{HH} = 8.3 Hz, 2H), 6.62 (d, J_{HH} = 8.8 Hz, 4H), 6.32 (t, J_{HH} = 7.6 Hz, 4H), 5.87 (d, J_{HH} = 6.9 Hz, 4H), 2.79 (t, J_{HH} = 7.3 Hz, 2H), 2.49 (dd, J_{HH} = 19.8, 12.6 Hz, 4H), 1.20 (s, 27H).

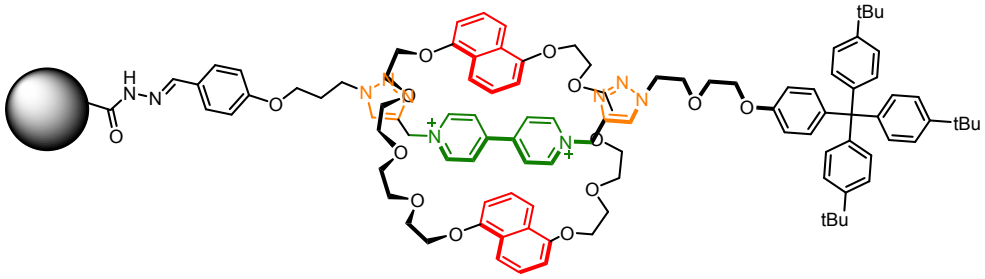
Synthesis of beads functionalised with bipyridinium dumbbell 21.2PF_6^-



A solution of bipyridinium half dumbbell **15.2PF_6^-** (75 mg, 55 µmol) in $CHCl_3$ (7 mL) with 0.1% TFA was added to the TentaGel™-$CONHNH_2$ resins **19** (0.27 mmol/g, 20 mg, 5.4 µmol). The suspension was stirred for 14 days before being quenched with aqueous $NaHCO_3$. The beads were then filtered and washed according to the general procedure for the hydrazide beads as well as several washes with aqueous NH_4PF_6 (2 M) before being dried. HR-MAS ^{1}H NMR (400 MHz, CD_3CN) δ 8.95 – 8.86 (m), 8.84 (s), 8.79 (s), 8.58 (d, J = 6.3 Hz), 8.36 – 8.29 (m), 8.13 – 8.04 (m), 7.87 – 7.75 (m), 7.66 – 7.54 (m), 7.37 – 7.23 (m), 7.22 – 7.05 (m), 6.99 – 6.86 (m), 6.86 –

6.71 (m), 2.64 – 2.57 (m), 2.45 – 2.33 (m), 2.18 – 2.13 (m), 1.28 (s). Due to broad signals, the peaks could not be unambiguously assigned (see Figure S26).

Synthesis of bipyridinium rotaxane functionalised resins 2.2PF_6^-



A solution of bipyridinium half dumbbell **15.2PF_6^-** (75 mg, 55 µmol) in $CHCl_3$ (7 mL) with 0.1% TFA was added to the TentaGel^{TM}-$CONHNH_2$ resins **19** (0.27 mmol/g, 20 mg, 5.4 µmol). To this suspension was added 1,5-dinaphtho[38]crown-10 **5** (266.5 mg, 0.42 mmol). The reaction mixture was stirred for 14 dayas before being quenched with aqueous $NaHCO_3$. The beads were then filtered and washed according to the general procedure for the hydrazide beads before being dried. HR MAS ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.97 (s), 8.83 (s), 8.78 (d, J = 5.8 Hz), 8.58 (d, J = 6.7 Hz), 8.34 (s), 8.13 – 8.04 (m), 7.86 – 7.76 (m), 7.75 – 7.67 (m), 7.67 – 7.55 (m), 7.31 (dd, J = 17.1, 8.6 Hz), 7.23 – 7.05 (m), 6.99 – 6.84 (m), 6.83 – 6.74 (m), 6.72 (d, J = 8.9 Hz), 6.65 – 6.56 (m), 2.82 (t, J = 7.1 Hz), 2.64 – 2.57 (m), 2.53 – 2.39 (m), 2.38 – 2.32 (m), 2.10 – 2.06 (m), 1.88 – 1.84 (m), 1.84 – 1.80 (m), 1.27 (s). Due to broad signals, the peaks could not be unambiguously assigned (see Figure S27).

HPLC and LC MS methods

HPLC-grade MeCN and isopropanol were filtered with a 0.45 μm Millipore filter, degassed appropriately and used without further purification. HPLC analysis was carried out on a Dionex Ultimate 3000 RSLC system coupled in parallel to a diode array detector and a Thermo Fisher Scientific Orbitrap Elite mass spectrometer, with the flow split ~4:1 by adjusting the dimensions of the connective tubing. The data was processed using Thermo Xcalibur software. ESI mass spectra in positive ion mode were acquired with a resolution 120000 (Δm/m, defined at *m/z* 400).

Table S1: ESI-MS Orbitrap source settings for the HPLC-MS studies of the exchange experiments.

ESI-MS parameters	
Heater temperature (°C)	300
Sheath Gas flow rate (arb.)	25
Aux Gas flow (arb.)	5
Sweep Gas flow rate (arb.)	1
Capillary temperature (°C)	350

Table S2: LC-UV-vis detector settings for the HPLC-MS studies of the exchange experiments.

Detection wavelength (nm)	Detection window (nm)	Reference wavelength (nm)	Reference window (nm)
254	8	600	8
292	8	600	8
380	8	600	8
420	8	600	8

Table S3: Reverse-phase HPLC gradient used to monitor the formation of the NDI dumbbell **11** and the NDI rotaxane **6** via hydrazone exchange. Solvent flow of 1 mL/min and column temperature set to 30°C.

Time (min)	% MeCN	% ^{i}Prop
0.0	75	25
2.0	75	25
12.0	50	50
15.0	50	50
17.0	0	100
19.0	0	100
21.0	75	25

Table S4: Reverse-phase HPLC gradient used to monitor the elution of bipyridinium half-dumbbell **15.PF_6^-**.

Time (min)	Aceonitrile 0.1 % FmAc (v/v)	Water 0.1 % FmAc (v/v)
2.0	70	30
4.0	80	20
17.0	85	15
19.0	85	15

2. Supplementary Schemes and Figures

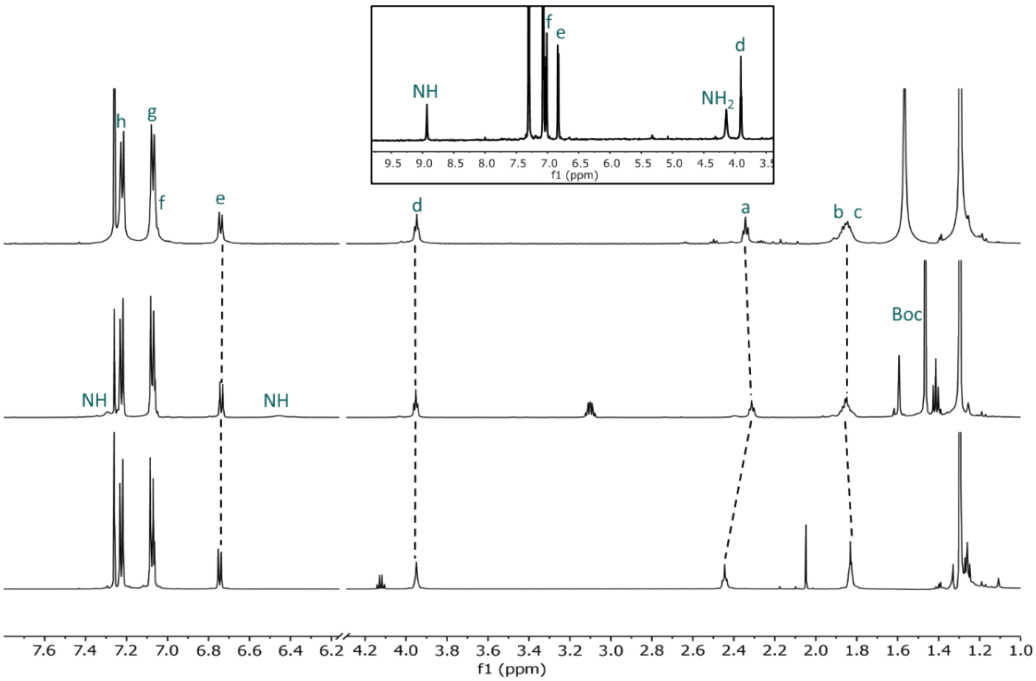
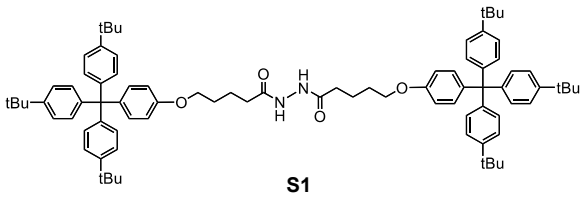


Figure S1: ^{1}H NMR ($CDCl_3$, 600 MHz) spectra of the hydrazide stopper **3** and its derivatives. Shown are the ^{1}H NMR spectra of the acid derivative **8** (bottom), the Boc protected hydrazide **9** (middle) and the final product **3** (top), with the insert showing the –NH and -NH_2 signals of the hydrazide in DMSO-d_6 (top). Deuterium exchange experiments were conducted on **3**, and upon addition of D_2O the signals at 8.93 ppm and 4.14 disappeared confirming that they are the hydrazido NH protons.



S1

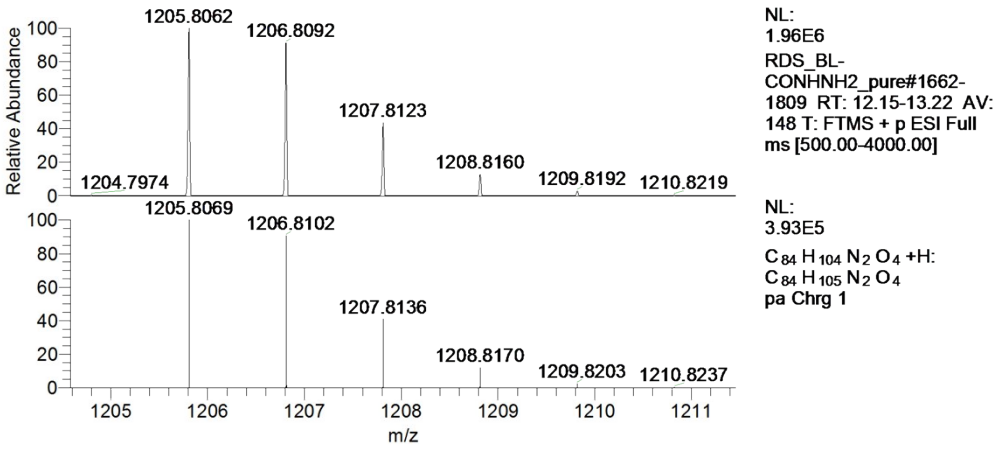


Figure S2: Mass distribution of ion $[M + H]^+$ of unreactive **S1** formed from the dimerization of hydrazide stopper **3**.

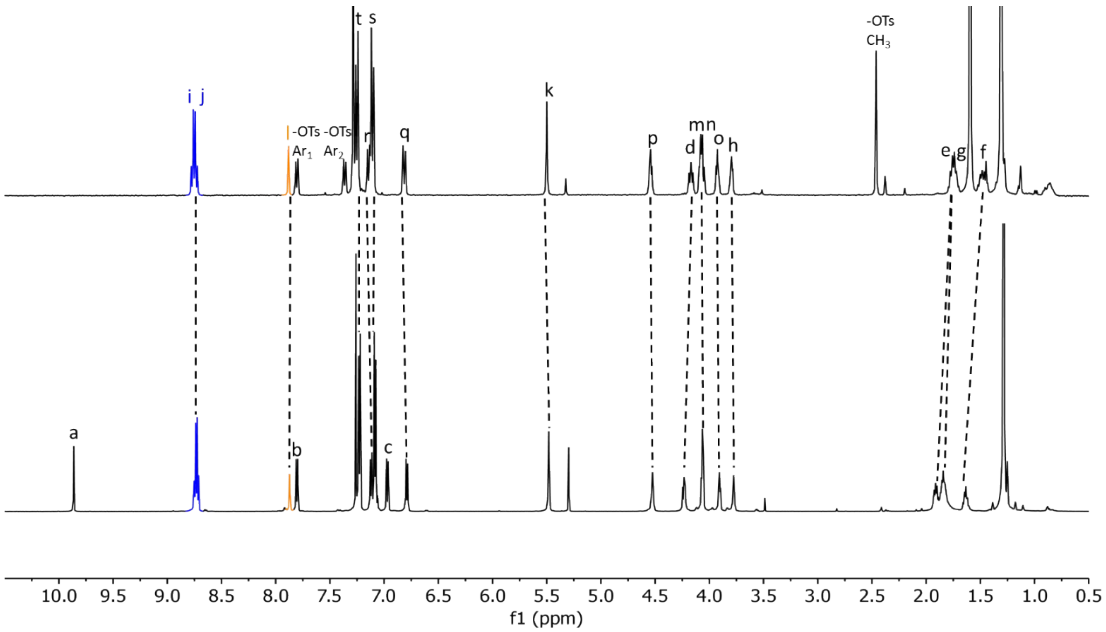


Figure S3: ^{1}H NMR comparison of the NDI tosylate half-dumbbell **10** (400 MHz, $CDCl_3$, top) and NDI aldehyde half-dumbbell **4** (600 MHz, $CDCl_3$, bottom). Note the new peaks for the appended aldehyde proton *a* at 9.86 ppm as well as the new aromatic proton peaks of the appended *p*-hydroxybenzaldehyde *b* and *c* at 7.80 ppm and 6.97 ppm respectively.

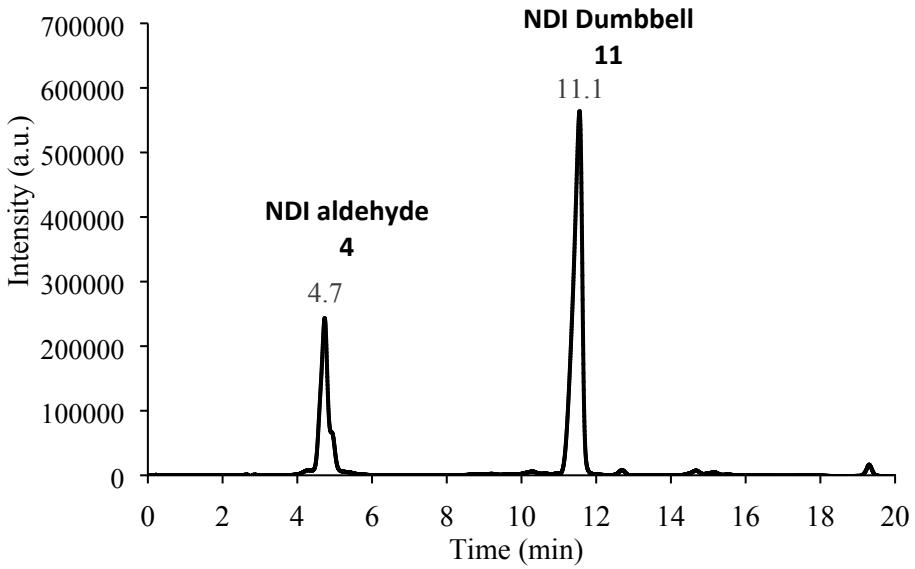


Figure S4: HPLC trace for the exchange between NDI half-dumbbell **4** and the hydrazide stopper **3** with 0.001 % TFA (recorded at 380 nm).

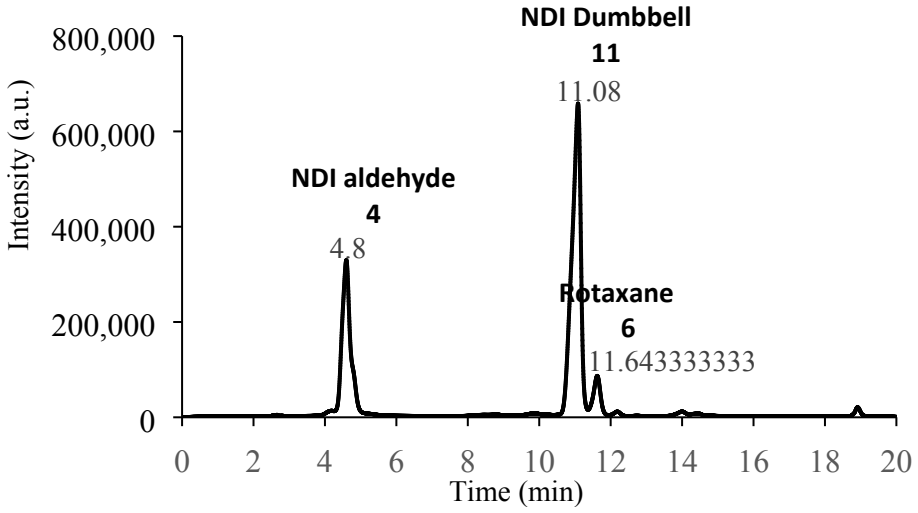


Figure S5: HPLC trace for the exchange between NDI half-dumbbell **4** and the hydrazide stopper **3** with 0.001 % TFA, 3 days after addition of one equivalent of macrocycle **5** (recorded at 380 nm).

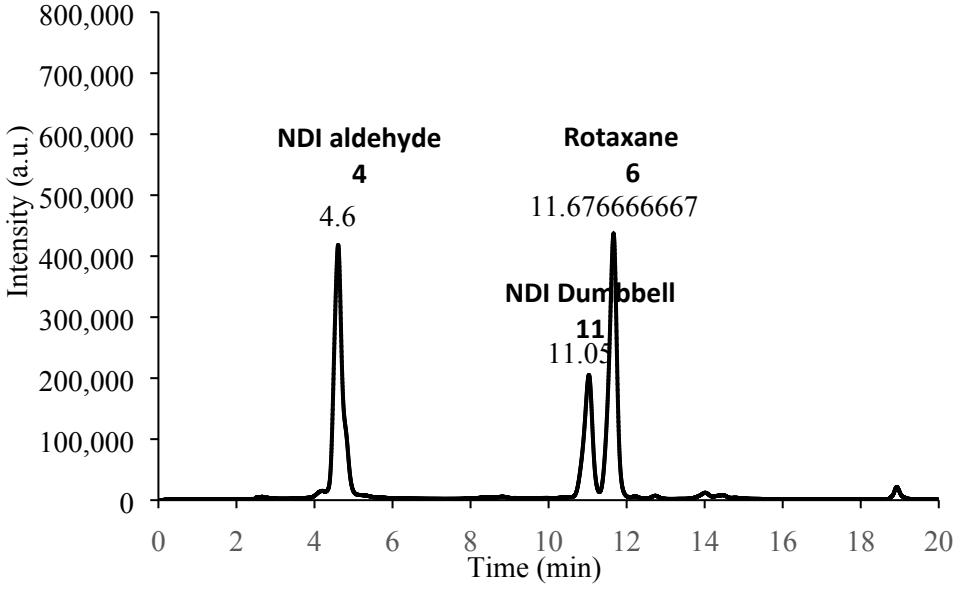


Figure S6: HPLC trace for the exchange between NDI half-dumbbell **4** and the hydrazide stopper **3** in the presence of 5 equivalents of DNQ[38]crown-10 **5** with 0.01 % TFA. HPLC trace recorded at 380 nm after 4 days of reaction.

Table S5: Monitoring the hydrazone exchange between NDI aldehyde **4** and hydrazide stopper **3** in the presence of 5 equivalents of macrocycle **5** with 0.1 % TFA catalyst. Normalised peak areas of residual aldehyde **4**, dumbbell **11** and rotaxane **6** over time as determined by HPLC at λ = 380 nm are reported.

% TFA	**Aldehdye 4** (4.7min) [%]		**Dumbbell 11** (11.1min) [%]		**Rotaxane 6** (11.7 min) [%]	
	6 days	14 days	6 days	14 days	6 days	14 days
0.1	43	44	17	14	40	42

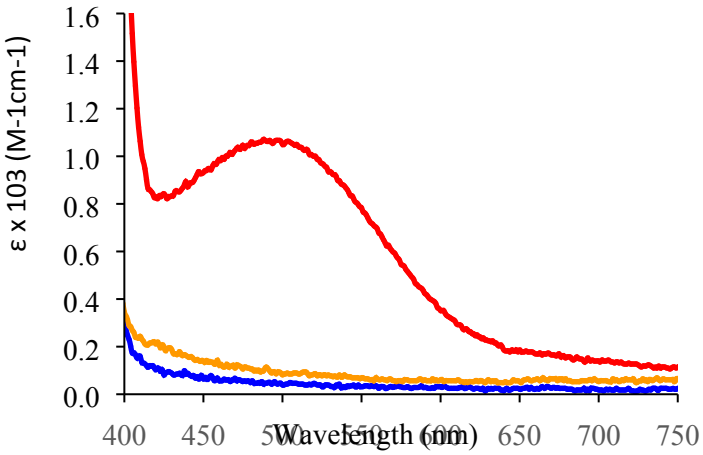


Figure S7: UV-vis absorption spectrum of the NDI half-dumbbell **4** (blue curve), the hydrazone dumbbell **11** (orange curve) and the hydrazone [2]rotaxane **6** (red curve) in $CHCl_3$.

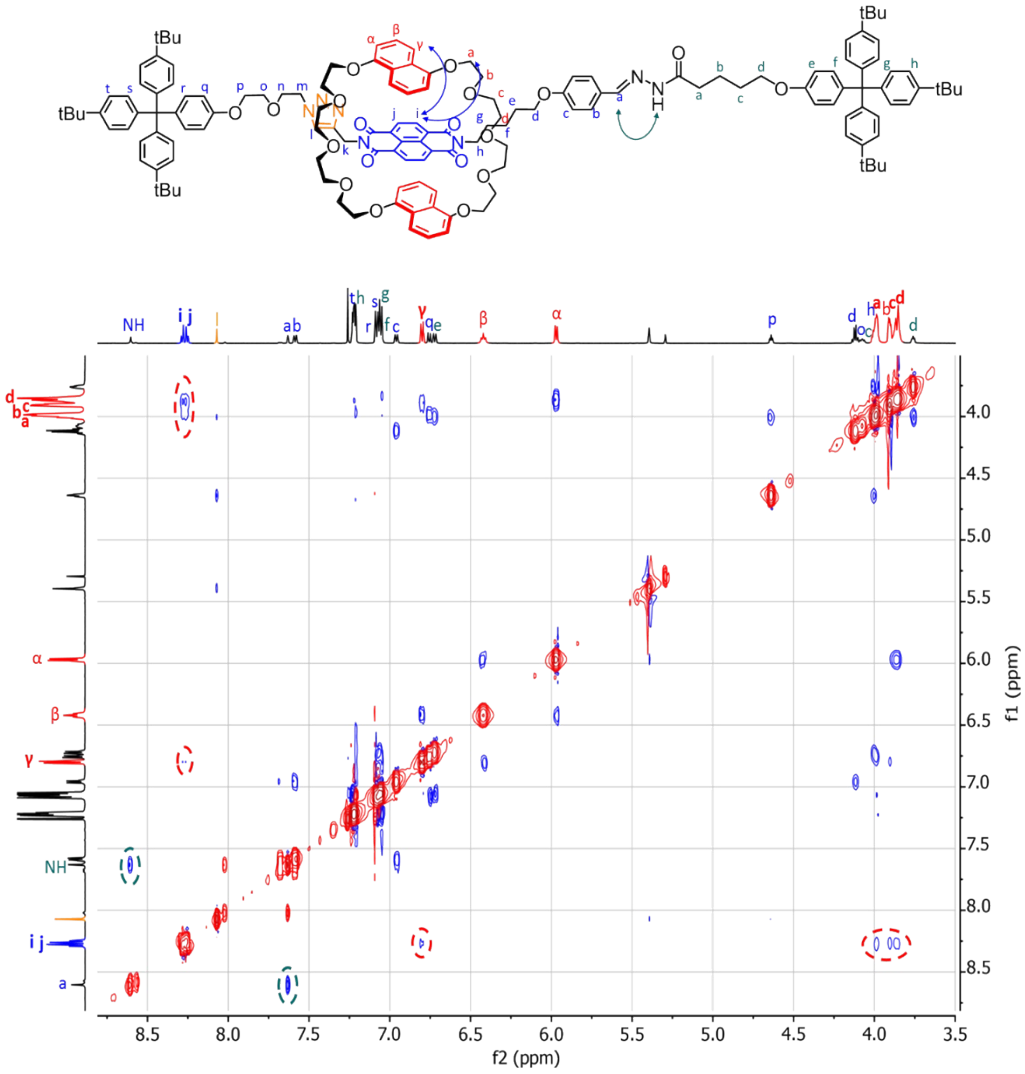


Figure S8: 2D-ROESY ^{1}H NMR ($CDCl_3$, 600 MHz) of [2]rotaxane **6** with cross-peaks between the dumbbell and the macrocycle highlighted with red dotted circles. Additional cross-peaks between proton -NH and proton a are highlighted with the teal circles.

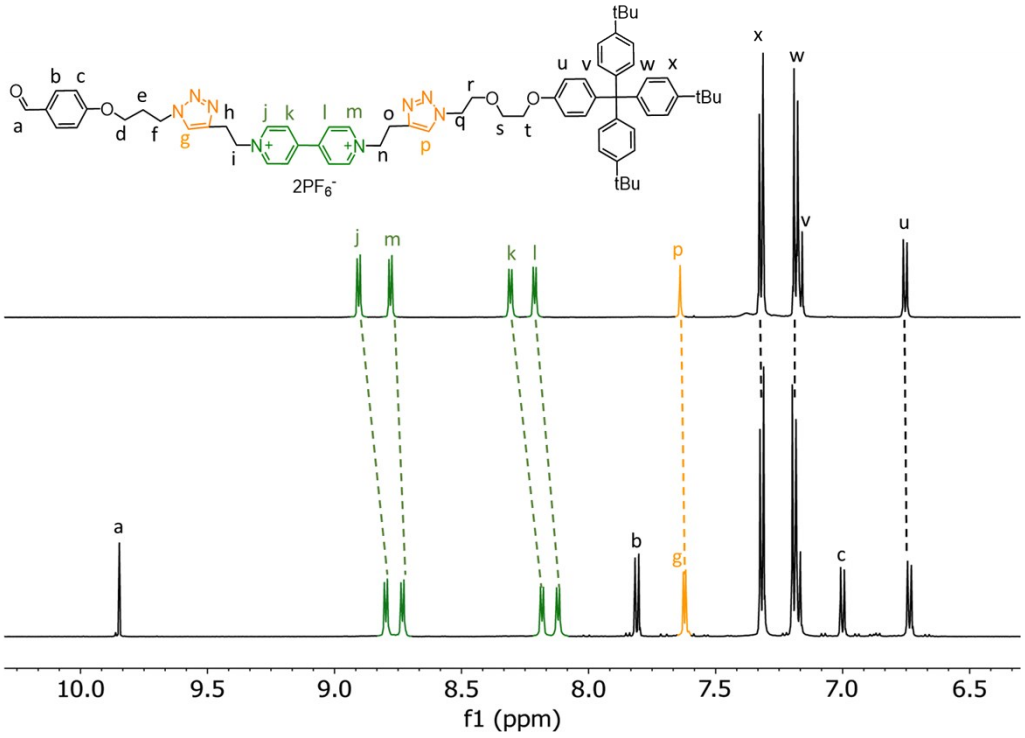


Figure S9: ^{1}H NMR comparison (CD_3CN, 600 MHz) of the bipyridinium alkyne half-dumbbell **14.2PF$_6^-$** (top) and the bipyridinium aldehyde half-dumbbell **15.2PF$_6^-$** (bottom). Note the new peaks for the appended aldehyde proton *a* at 9.77 ppm as well as the new aromatic proton peaks of the appended *p*-hydroxybenzaldehyde *b* and *c* at 7.73 ppm and 6.96 ppm respectively.

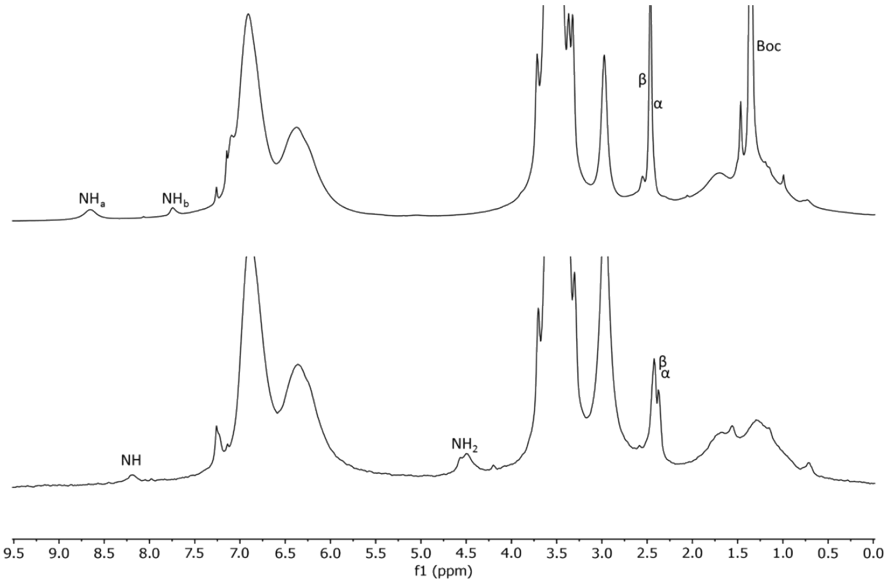
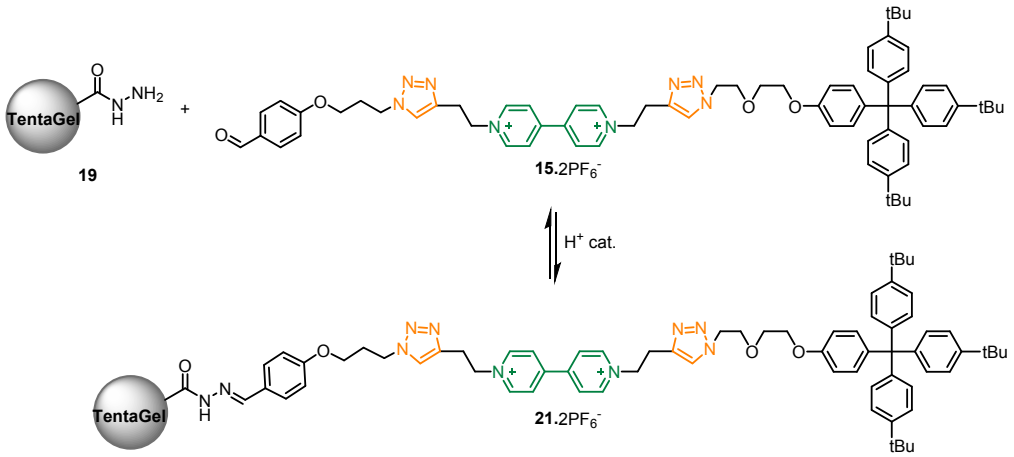
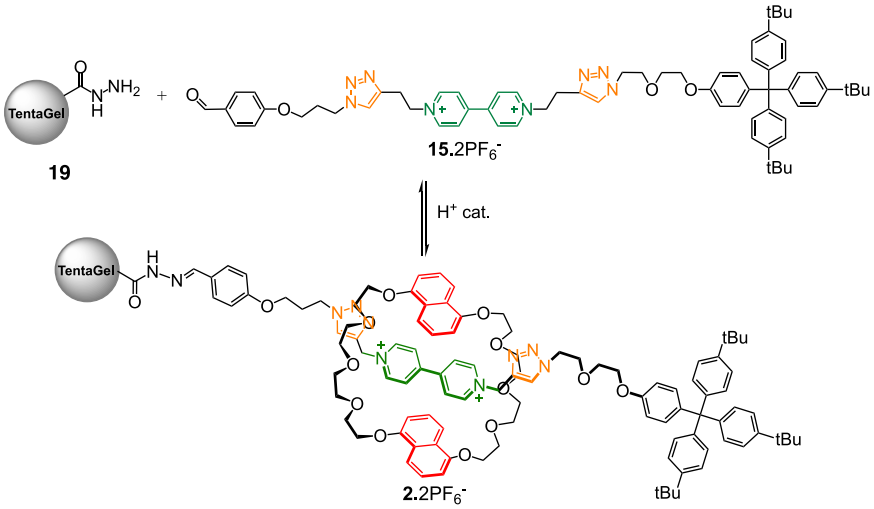


Figure S10: HR-MAS ^{1}H NMR spectra (400 MHz, $CDCl_3$, no CPMG sequence) of TentaGel^{TM} -CONHNHBoc resins **18** (top) and TentaGel^{TM} -CONHNH$_2$ resins **19** (bottom). Note, a CPMG pulse sequence was not used to characterise these resins to ensure the broad NH proton peaks could be identified.



Scheme S1: Synthesis of bipyridinium dumbbell functionalised TentaGel™ beads **21.2PF$_6^-$**. Reagents and conditions: TFA 0.1%, $CHCl_3$, 14 days.



Scheme S2: Synthesis of bipyridinium rotaxane functionalised TentaGel™ beads **2.2PF$_6^-$**. Reagents and conditions: **5** (5 equiv.), TFA 0.1%, $CHCl_3$, 14 days.

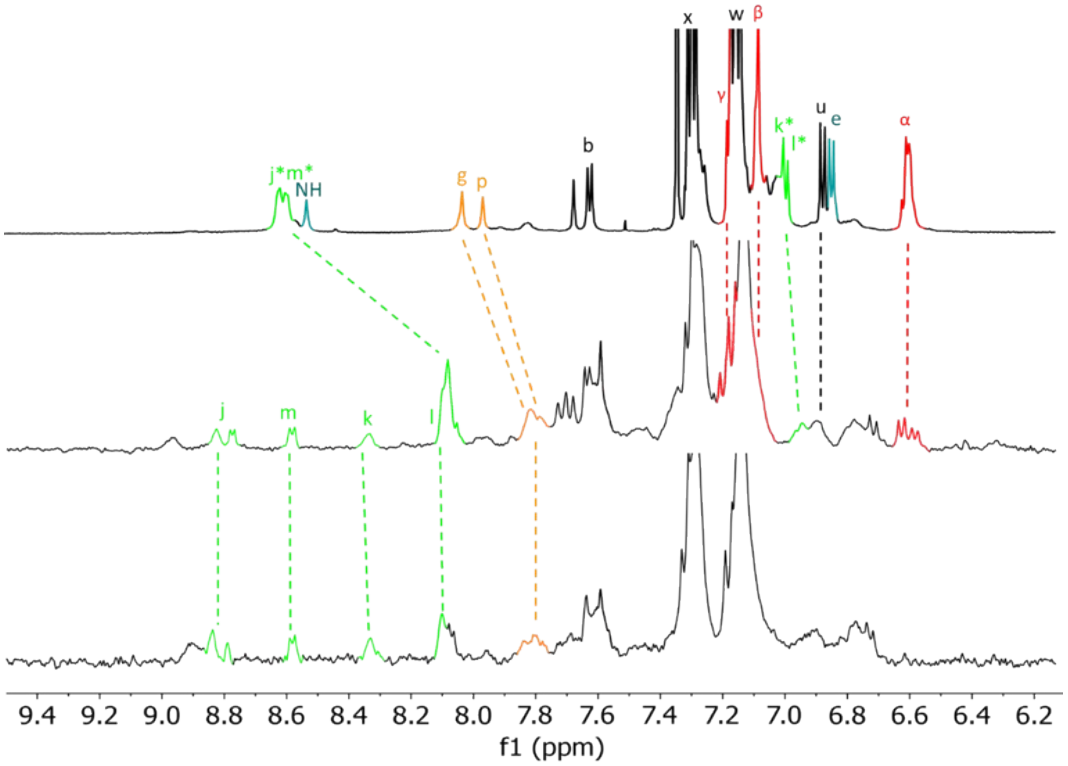


Figure S11: Comparison of the ^{1}H NMR spectrum (600 MHz, $CDCl_3$) of the bipyridinium [2]rotaxane **17.2PF$_6^-$** (top), the HR-MAS ^{1}H NMR spectra (400 MHz, CD_3CN, 128 CPMG loops) of the bipyridinium rotaxane functionalised beads **2.2PF$_6^-$** (middle) and the bipyridinium dumbbell functionalised resins **21.2PF$_6^-$** (bottom).

3. ^{1}H, ^{13}C NMR, HPLC and Mass Spectra of Select Molecules

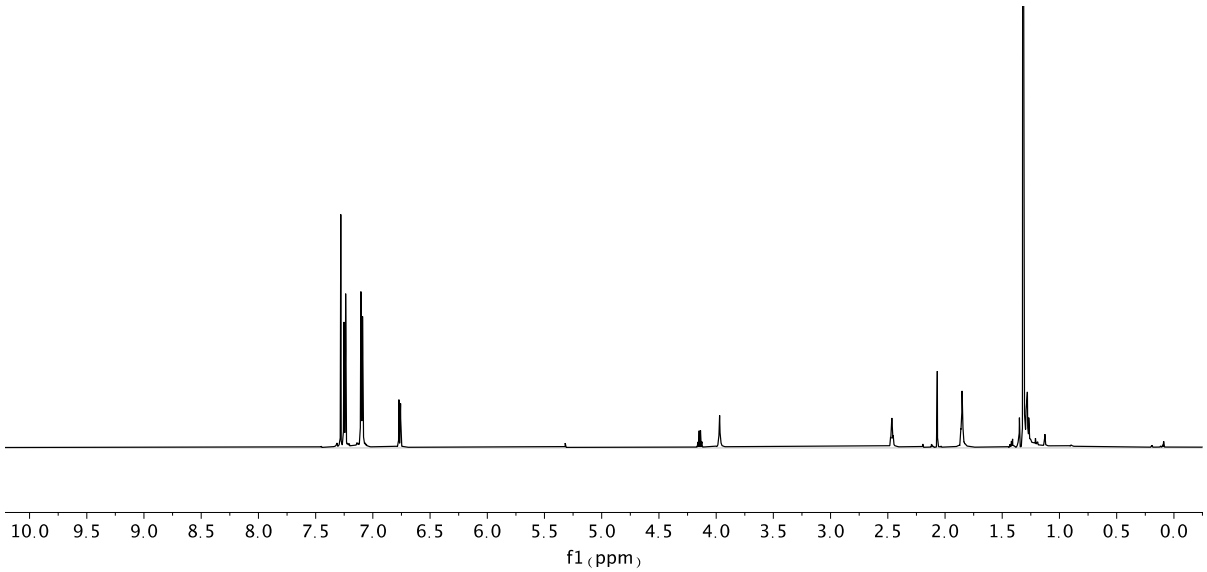


Figure S12: ^{1}H NMR spectrum (600 MHz, $CDCl_3$) of 5-(4-(Tris(4-(*tert*-butyl)phenyl)methyl)phenoxy)pentanoic acid **8**.

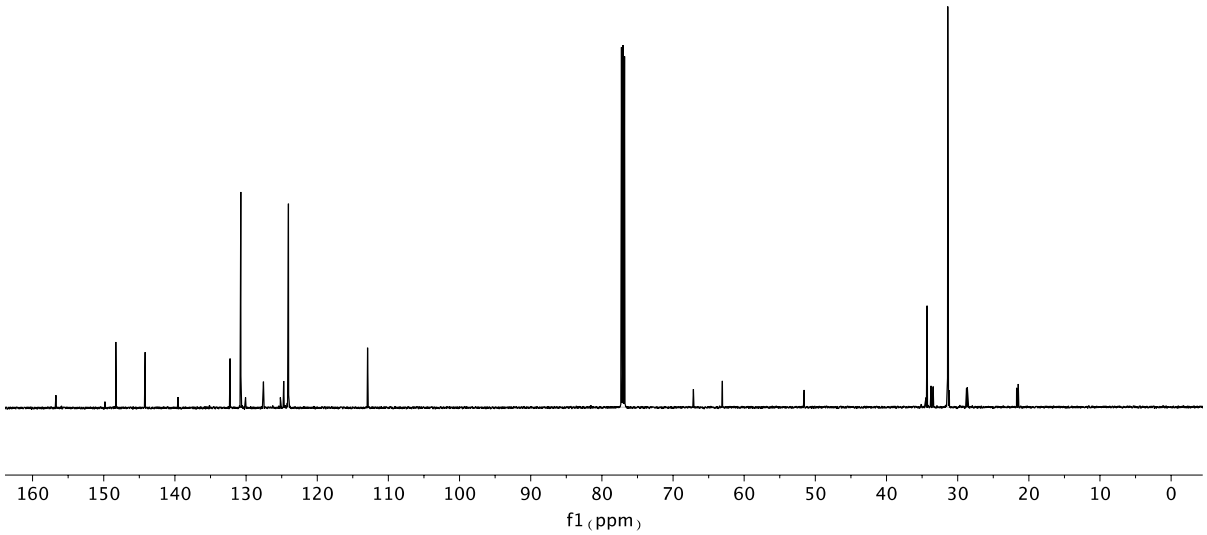


Figure S13: ^{13}C NMR spectrum (151 MHz, $CDCl_3$) of 5-(4-(Tris(4-(*tert*-butyl)phenyl)methyl)phenoxy)pentanoic acid **8**.

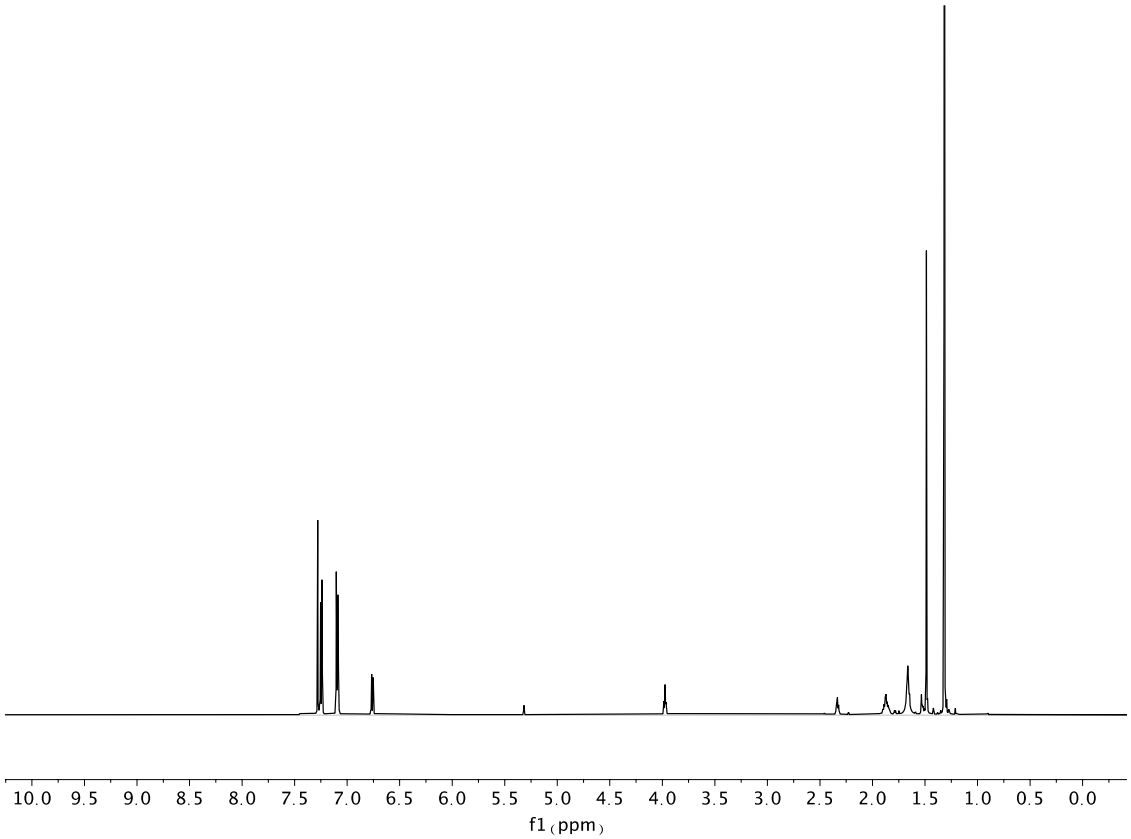


Figure S14: ^{1}H NMR spectrum (600 MHz, $CDCl_3$) of Boc protected hydrazide stopper **9**.

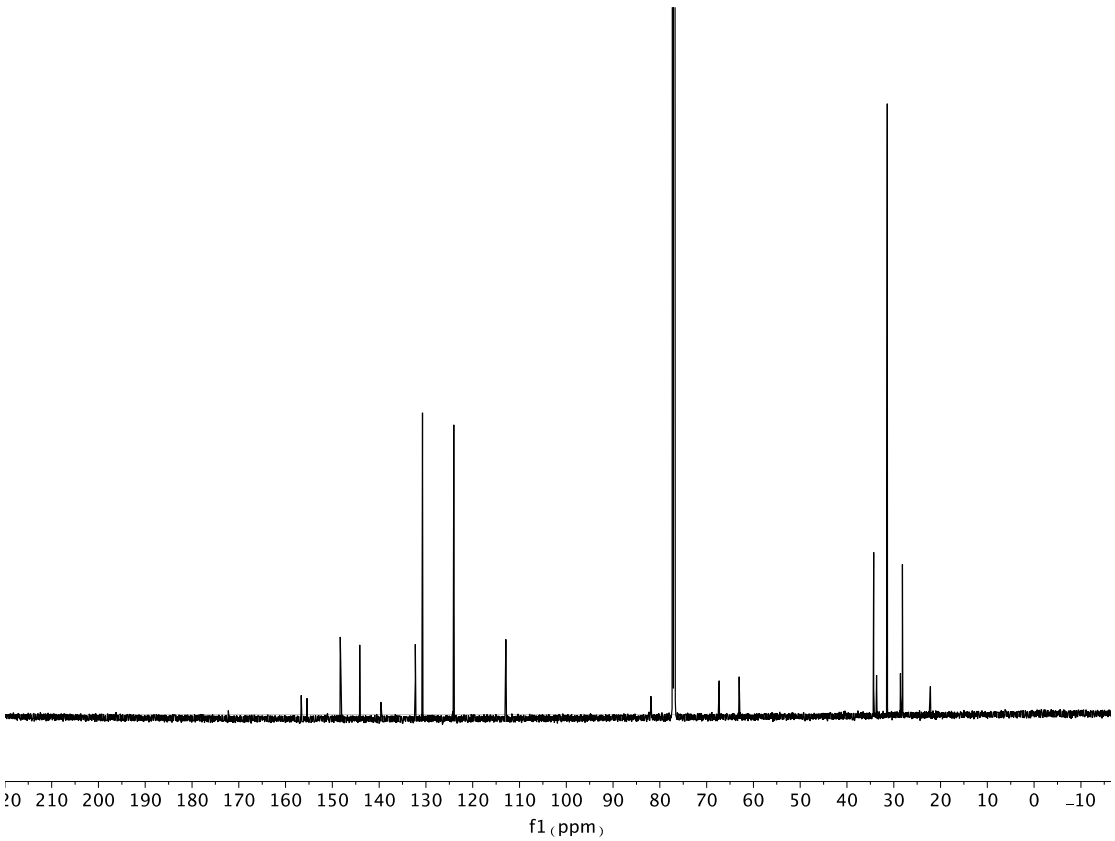


Figure S15: ^{13}C NMR spectrum (151 MHz, $CDCl_3$) of Boc protected hydrazide stopper **9**.

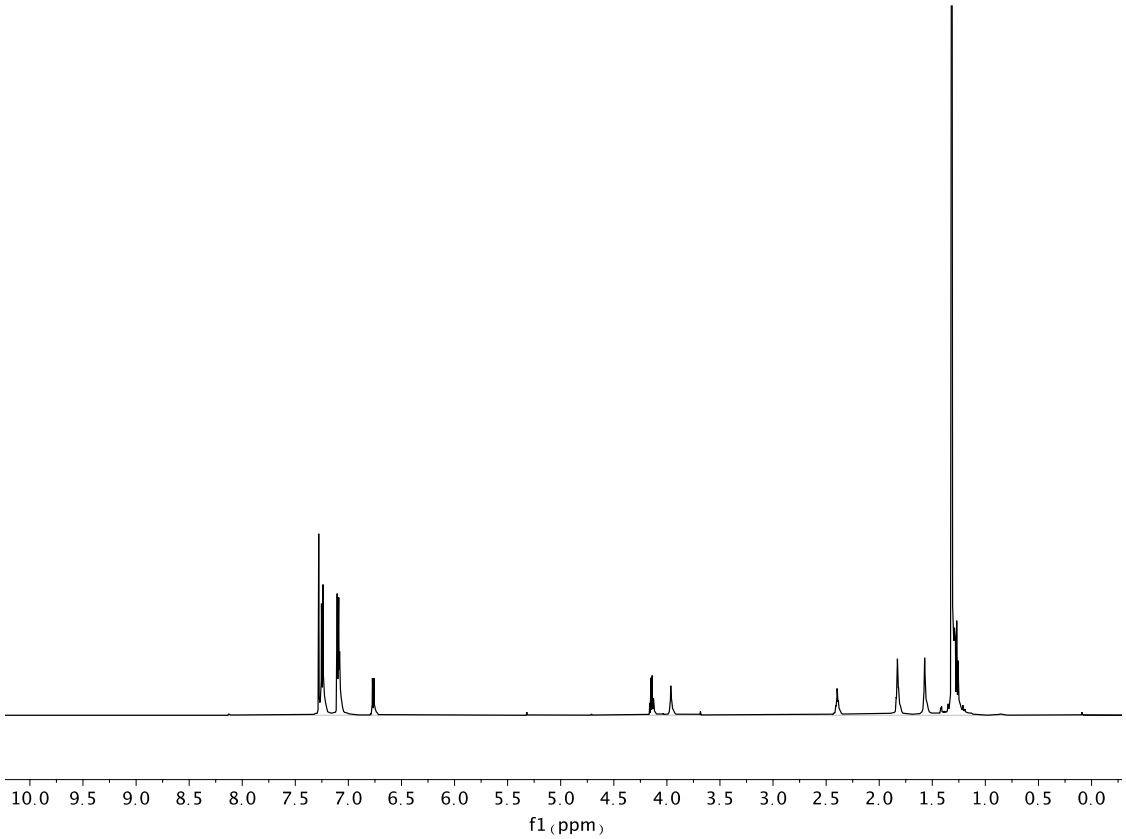


Figure S16: ^{1}H NMR spectrum (600 MHz, $CDCl_3$) of hydrazide stopper **3**.

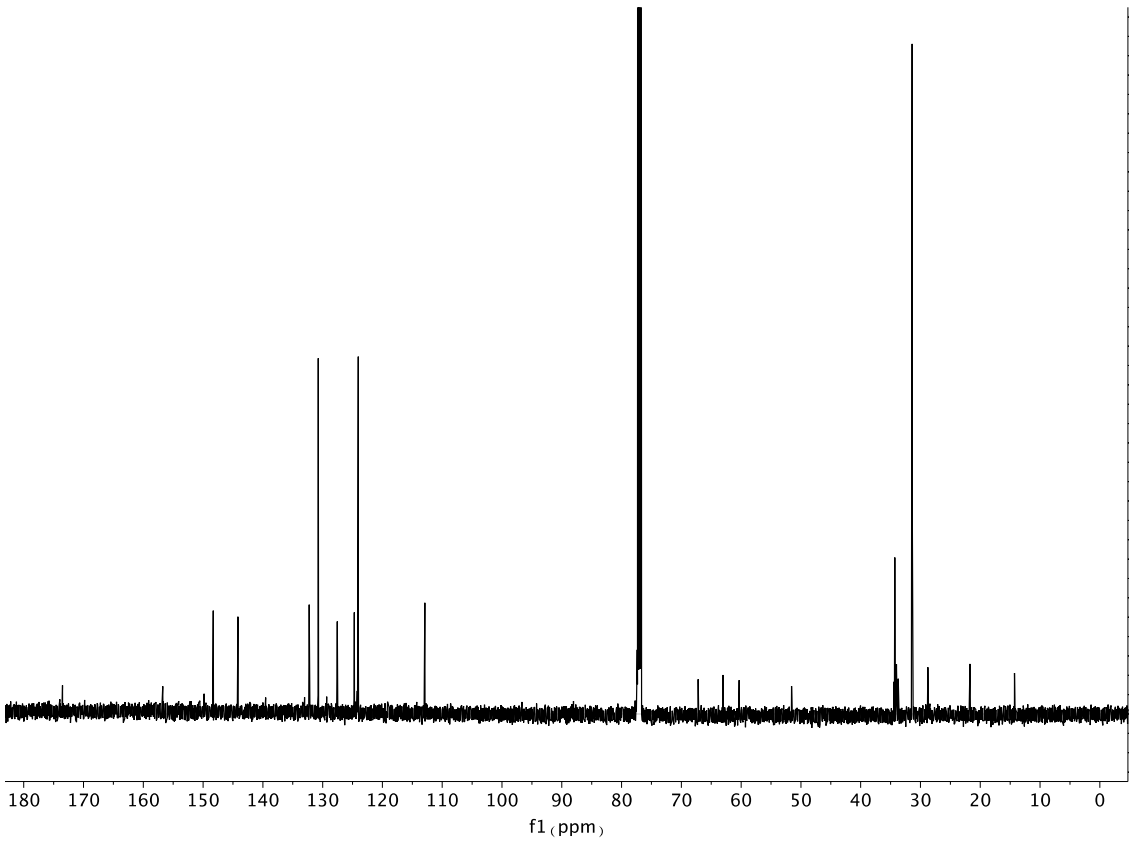


Figure S17: ^{13}C NMR spectrum (151 MHz, $CDCl_3$) of hydrazide stopper **3.**

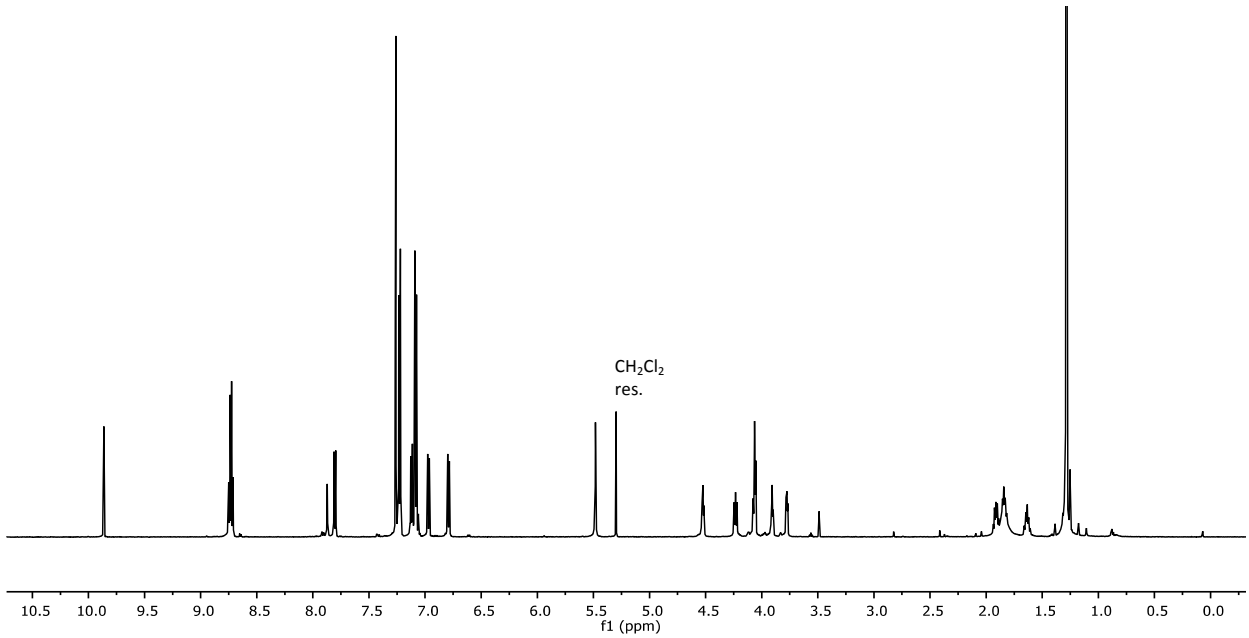


Figure S18: ^{1}H NMR spectrum (600 MHz, $CDCl_3$) of NDI aldehyde half-dumbbell **4**.

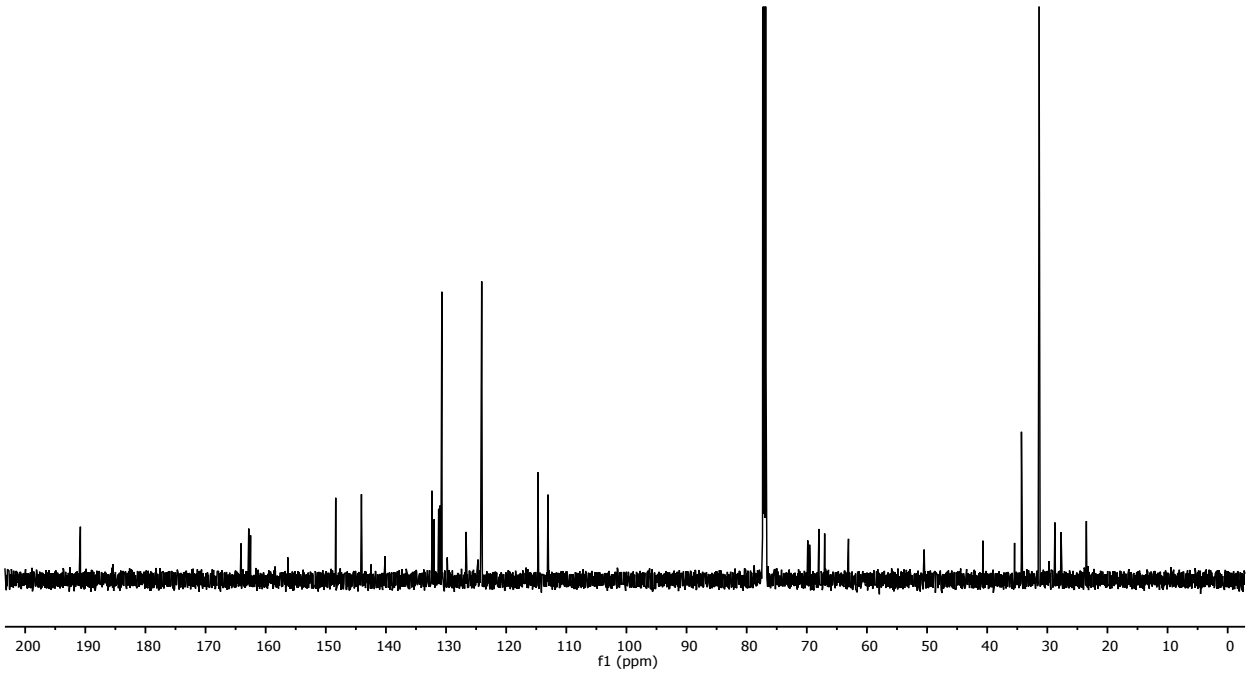


Figure S19: ^{13}C NMR spectrum (151 MHz, $CDCl_3$) of NDI aldehyde half-dumbbell **4**.

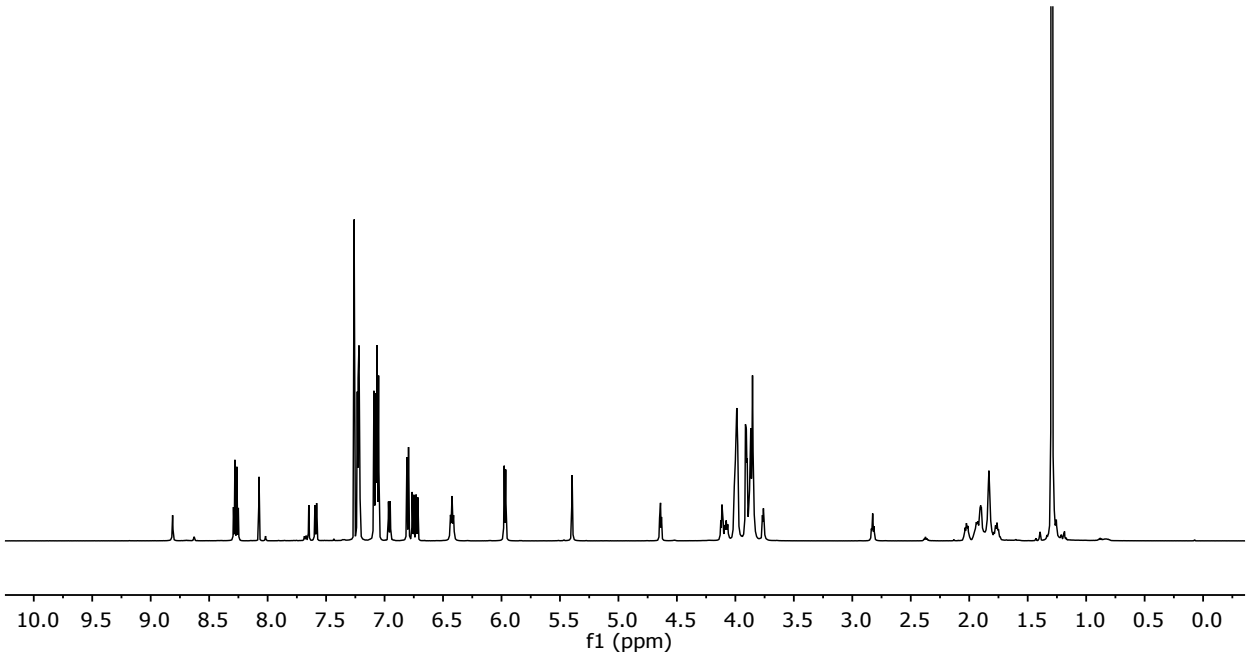


Figure S20: ^{1}H NMR spectrum (600 MHz, $CDCl_3$) of NDI rotaxane **6**.

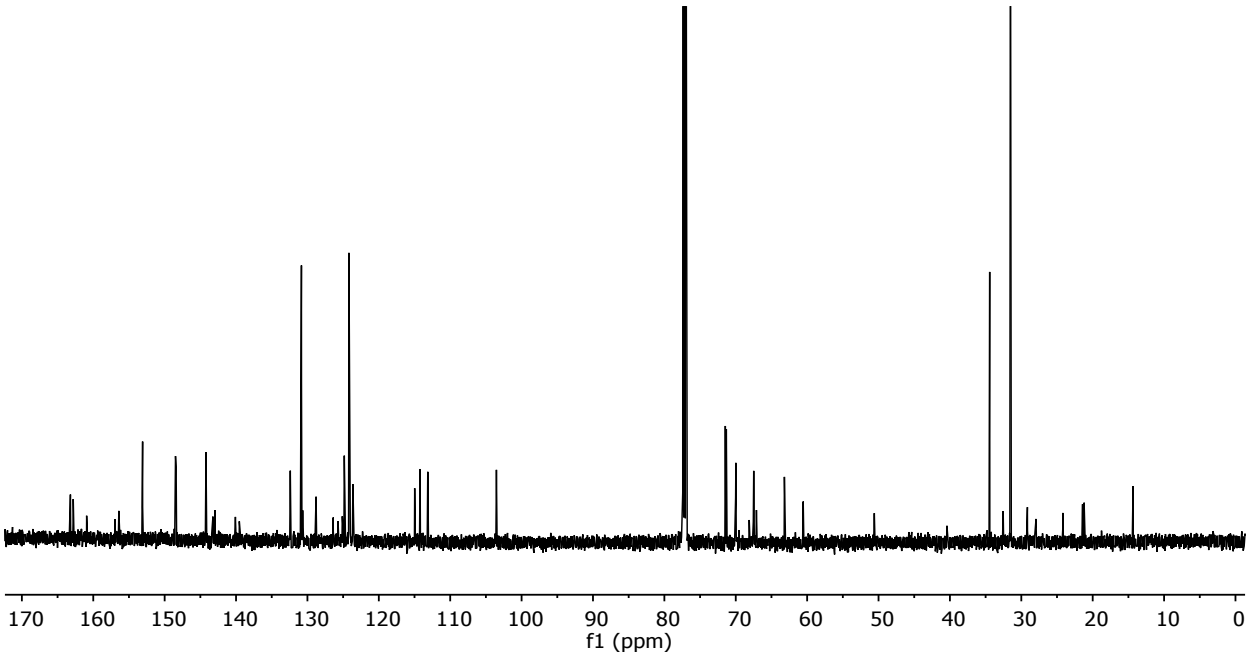


Figure S21: ^{13}C NMR spectrum (151 MHz, $CDCl_3$) of NDI rotaxane **6**.

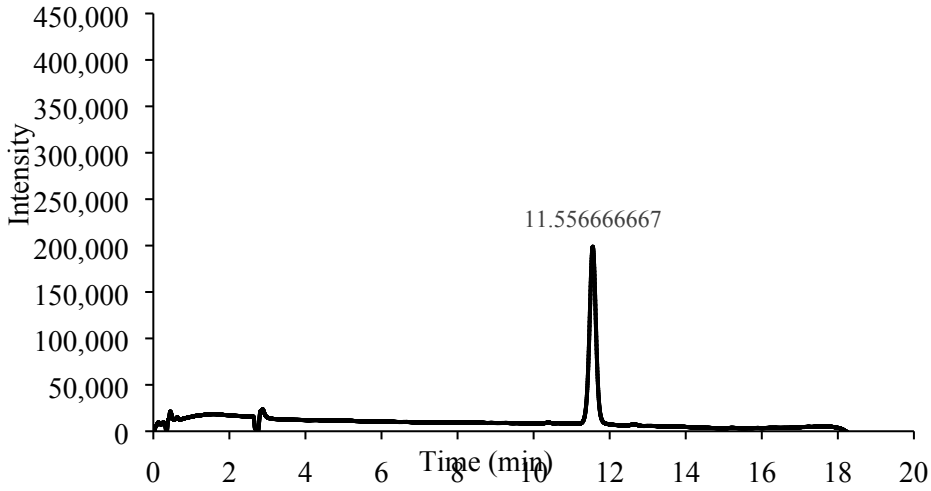


Figure S22: HPLC trace of the purified NDI rotaxane **6**.

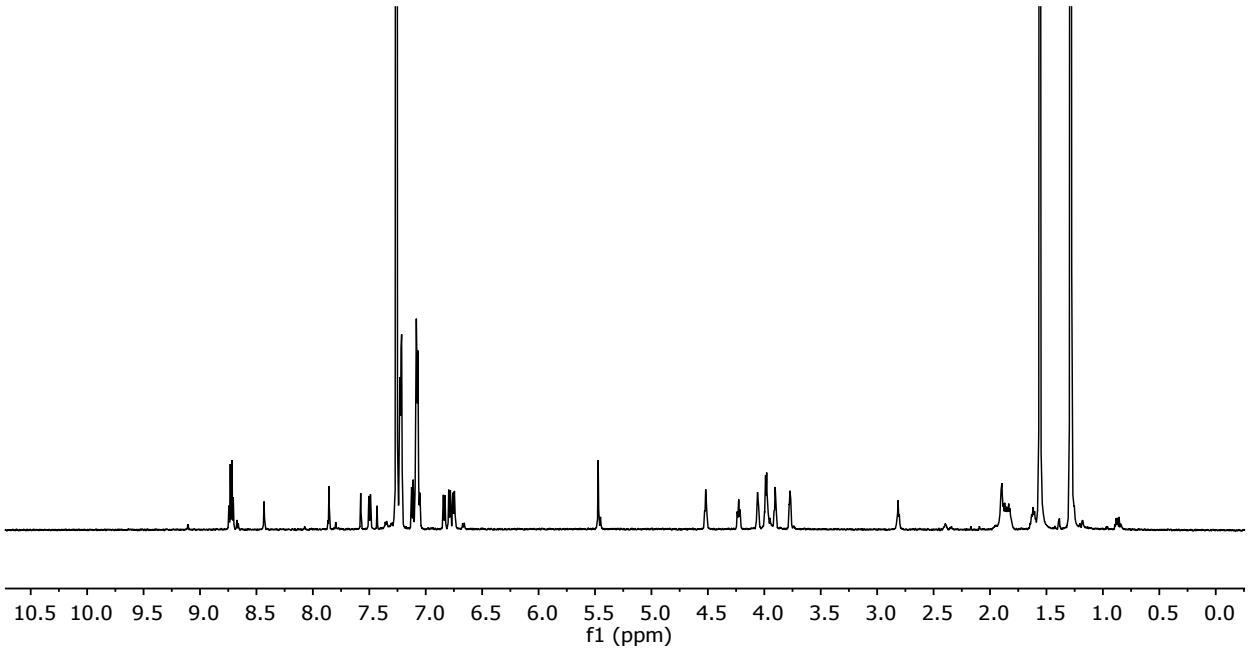


Figure S23: ^{1}H NMR spectrum (600 MHz, $CDCl_3$) of NDI hydrazone dumbbell **11**.

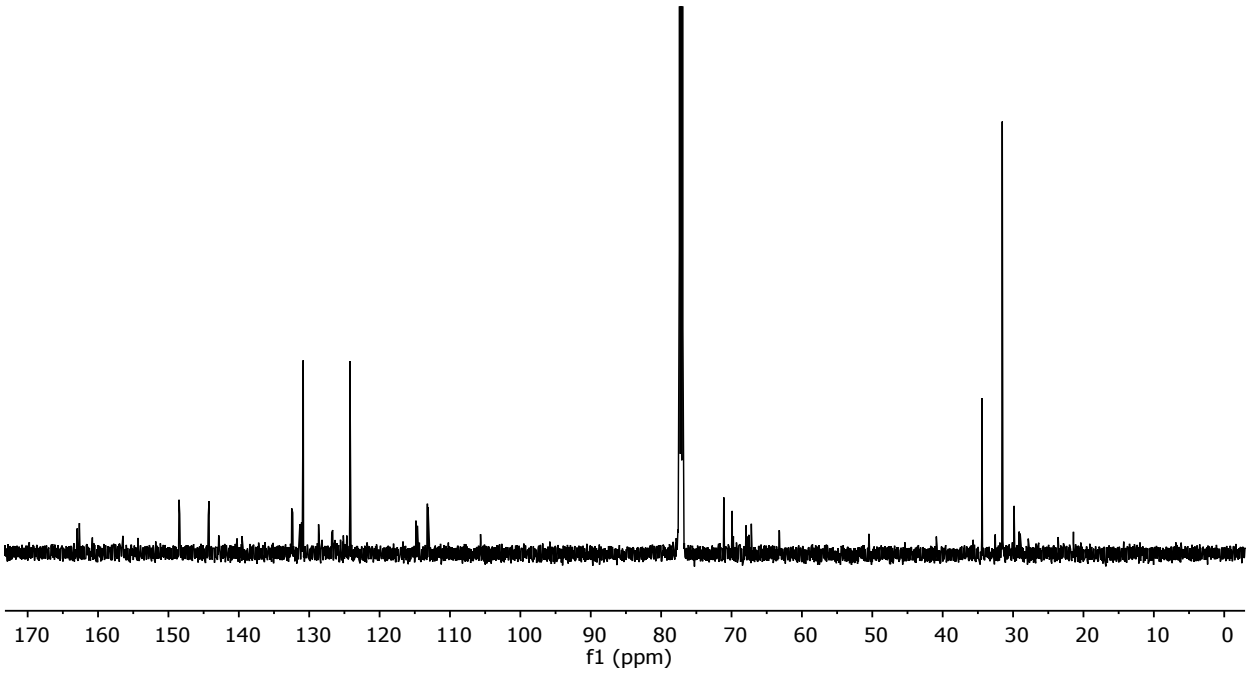


Figure S24: ^{13}C NMR spectrum (151 MHz, $CDCl_3$) of NDI hydrazone dumbbell **11**.

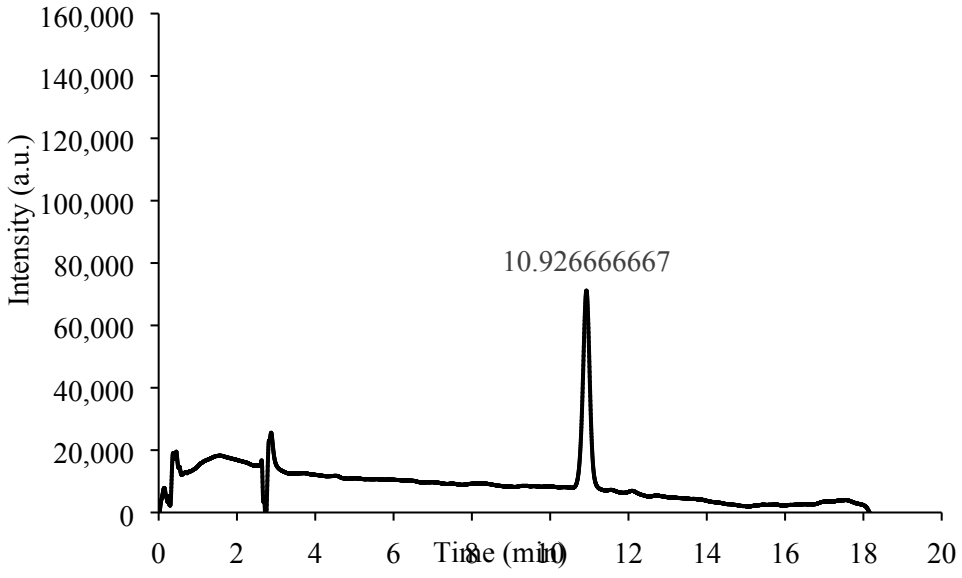


Figure S25: HPLC trace of the purified NDI hydrazone dumbbell **11**.

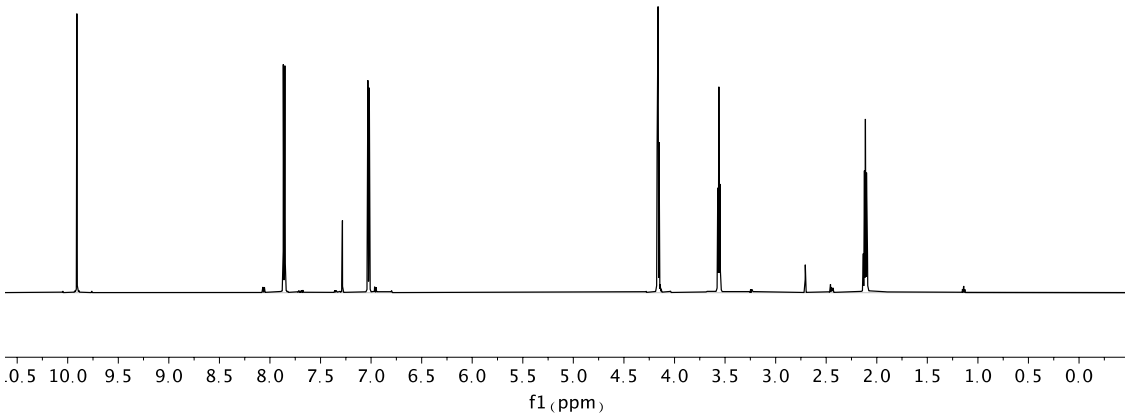


Figure S26: ^{1}H NMR spectrum (600 MHz, $CDCl_3$) of **13**.

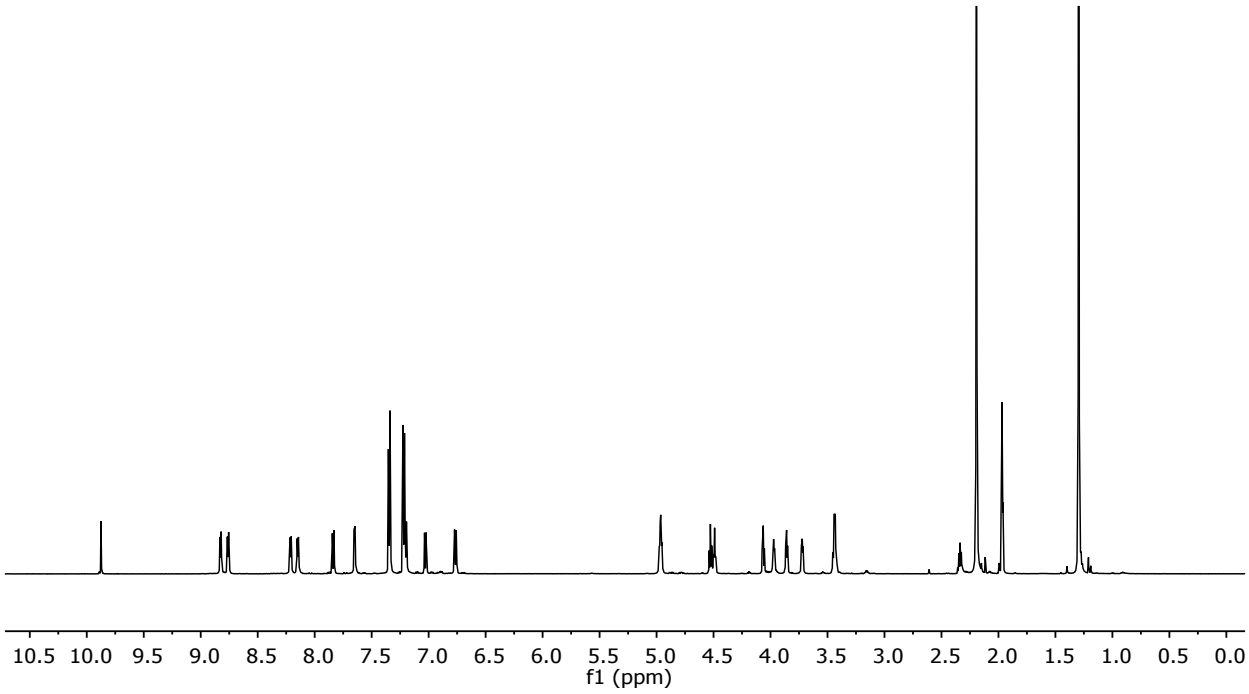


Figure S27: ^{1}H NMR spectrum (600 MHz, CD_3CN) of bipyridinium aldehyde half dumbbell **15.2PF$_6^-$**.

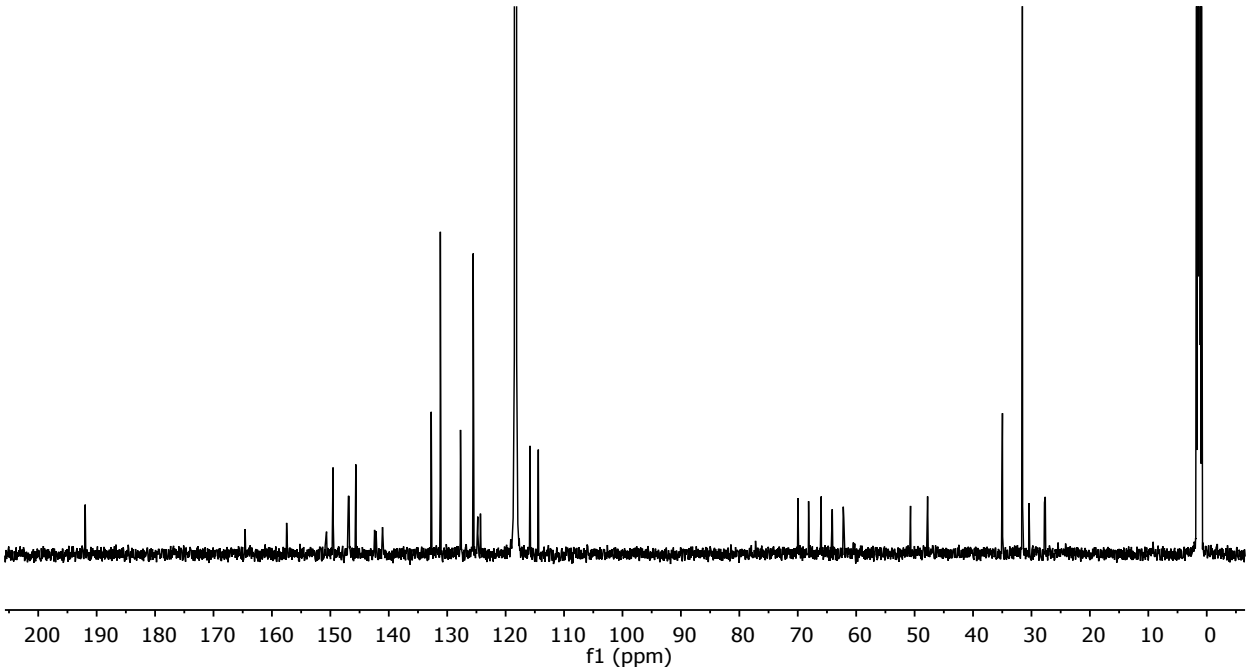


Figure S28: ^{13}C NMR spectrum (151 MHz, CD_3CN) of bipyridinium aldehyde half dumbbell **15.2PF$_6^-$**.

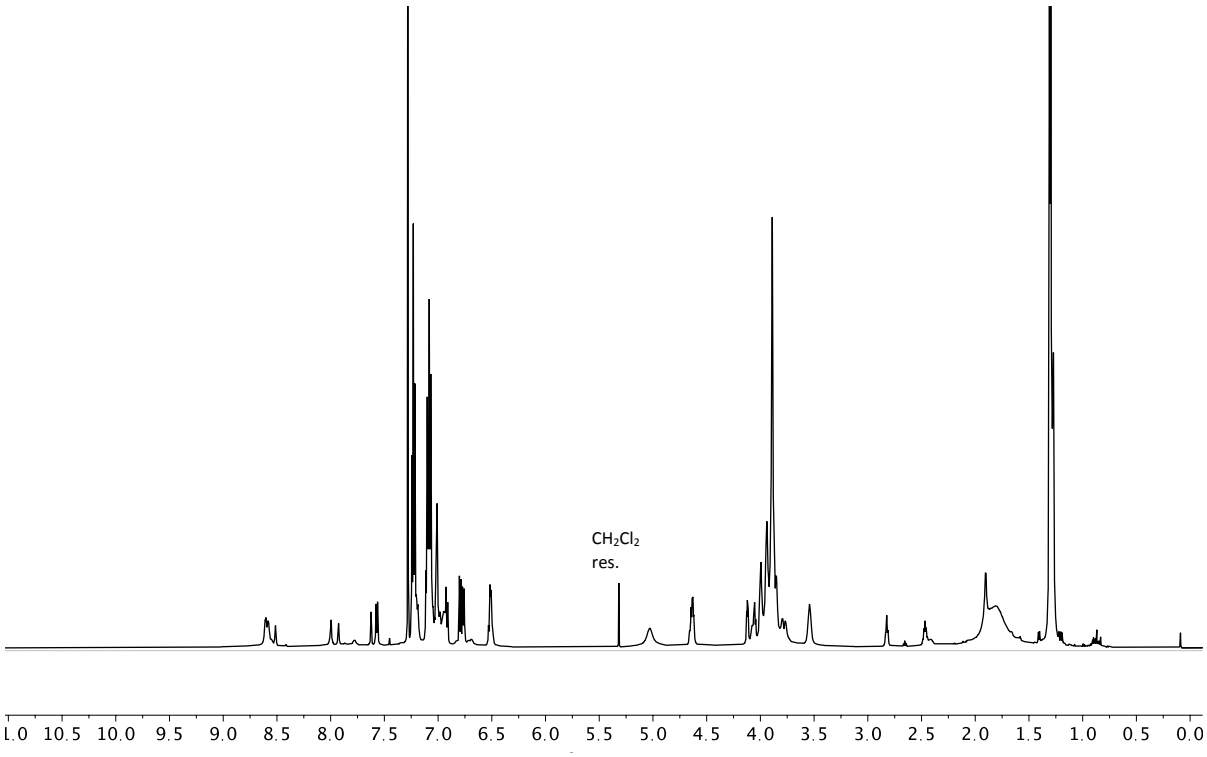


Figure S29: ^{1}H NMR spectrum (600 MHz, $CDCl_3$) of bipyridinium rotaxane **17.2PF$_6^-$**.

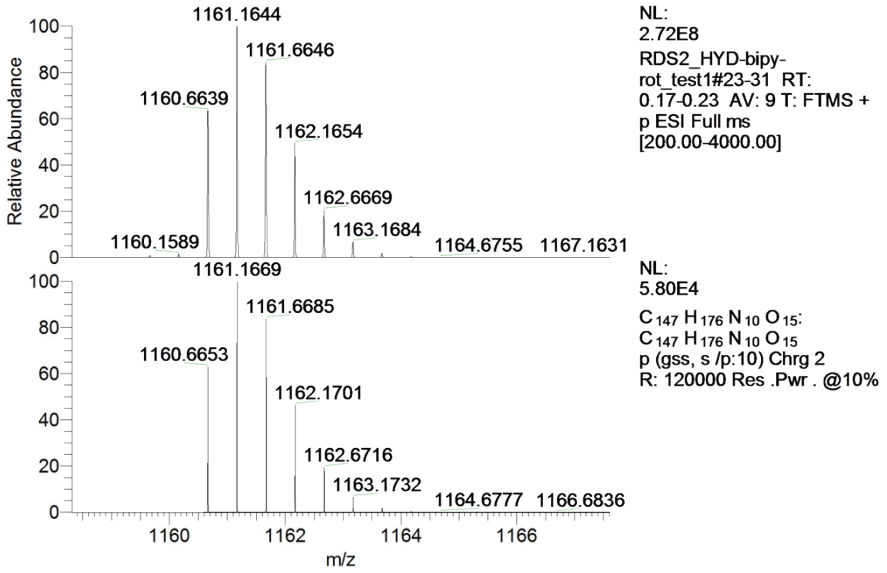


Figure S30: ESI-MS of bipyridinium rotaxane **17.2PF$_6^-$** [M - 2PF$_6^-$]$^{2+}$ (top) and simulated isotopic profile (bottom).

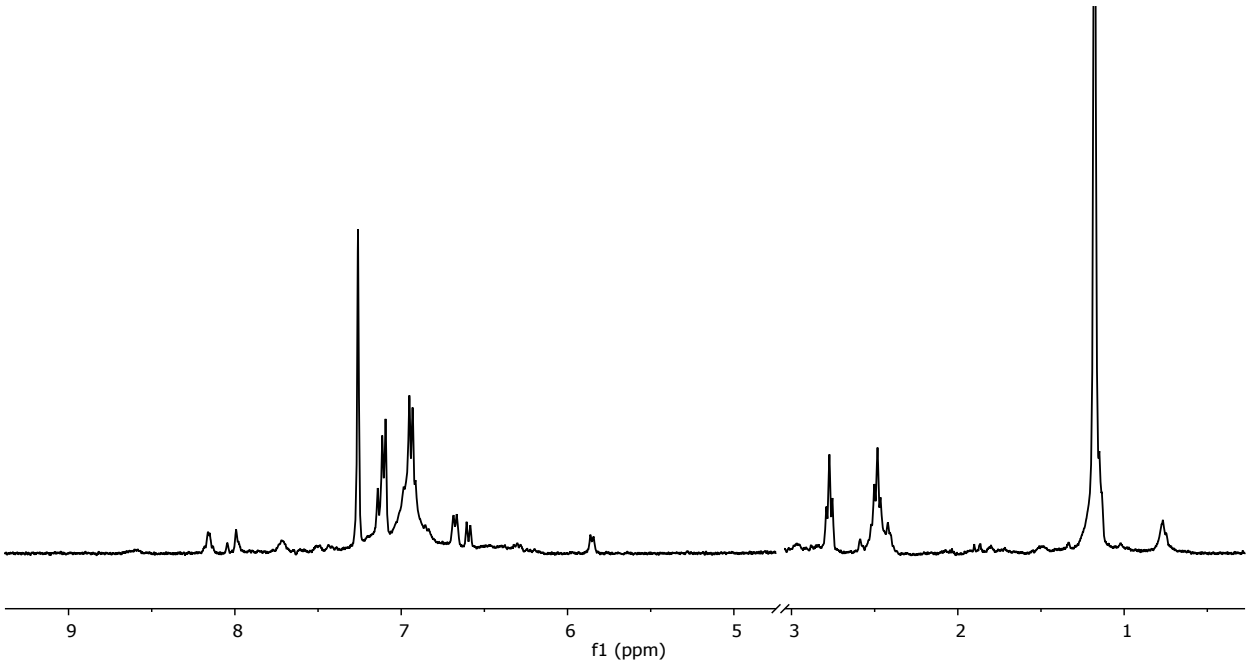


Figure S31: HR MAS ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of NDI dumbbell functionalised resins **20**. Resonances corresponding to the polystyrene beads have been omitted for clarity.

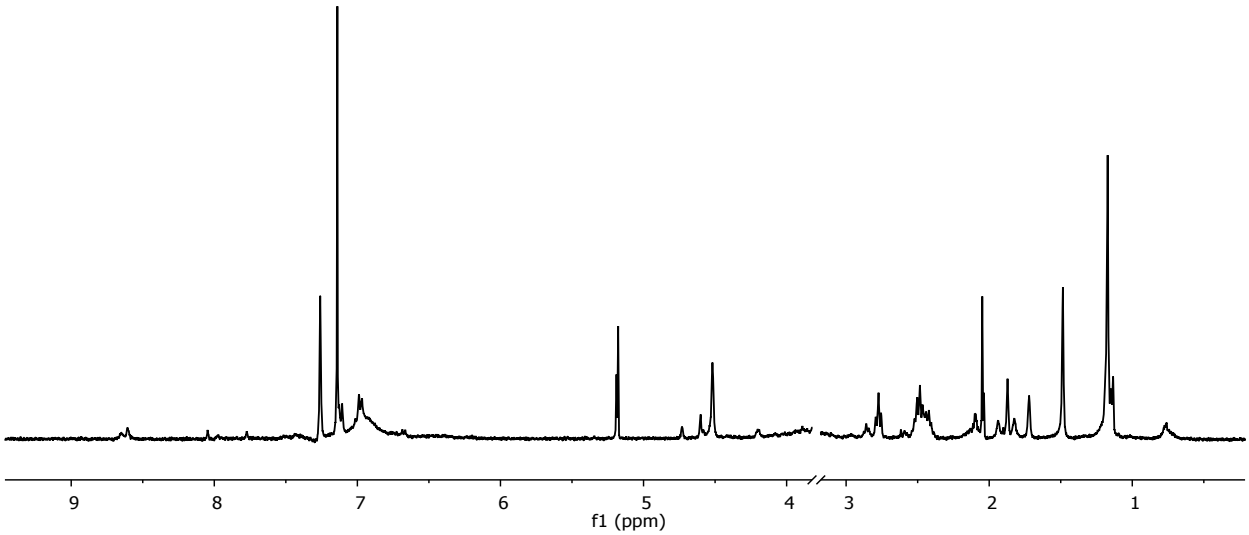


Figure S32: HR MAS ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of NDI rotaxane functionalised resins **1**. Resonances corresponding to the polystyrene beads have been omitted for clarity.

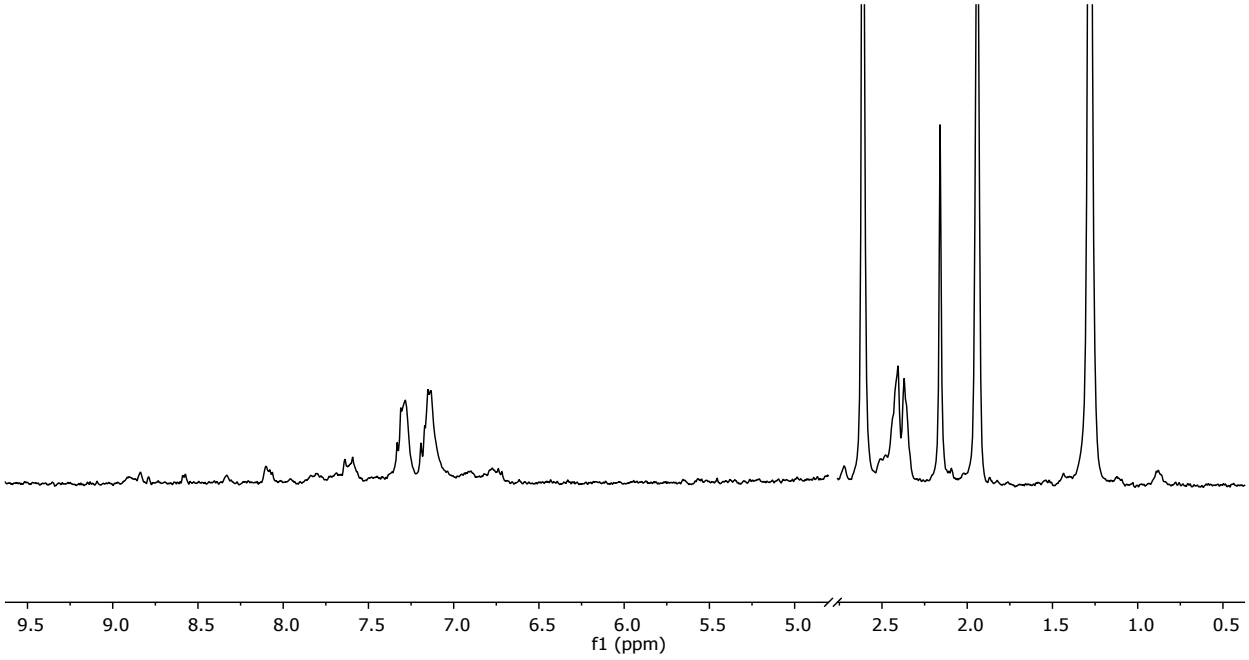


Figure S33: HR MAS ^{1}H NMR spectrum (400 MHz, CD_3CN) of bipyridinium dumbbell functionalised resins **21.2PF$_6^-$**. Resonances corresponding to the polystyrene beads have been omitted for clarity.

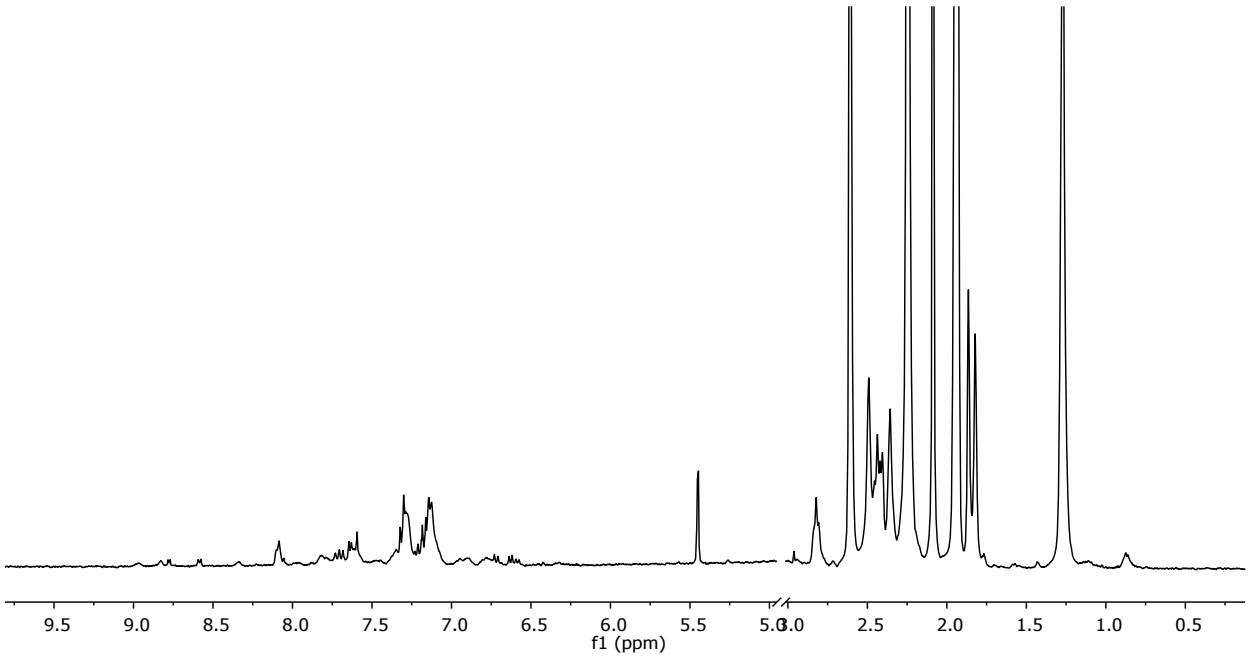


Figure S34: HR MAS ^{1}H NMR spectrum (400 MHz, CD_3CN) of bipyridinium rotaxane functionalised resins **2.2PF$_6^-$.** Resonances corresponding to the polystyrene beads have been omitted for clarity.

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